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1 **Title:**

2 The Blaster: A Methodology to Induce Rice Lodging at Plot Scale to Study Lodging Resistance

3

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12

13 **Abstract**

14 Lodging is a major yield-reducing factor in rice systems, particularly under intensified cultivation using  
15 high-yielding cultivars. It is usually triggered by rainstorms during grain filling. The study of natural  
16 lodging is difficult due to unpredictable weather. Proxy traits for lodging resistance such as stem  
17 morphology and breaking moment have limited validity because lodging is complex. We present a new  
18 mobile, low-cost field methodology called Blaster. It uses a wind turbine creating a 1m wide and 6m  
19 deep wind path in the field with wind speed adjustable to 30, 45 and 60 km h<sup>-1</sup>. Water injected into  
20 the air stream provides for wetting of the crop. A measurement cycle takes ca. 10 min per plot. The  
21 lodging response of 20, mostly high-yielding but diverse rice genotypes was studied in 2013, 2014 and  
22 2015 under irrigated transplanted conditions in the Philippines. Genotypic responses were  
23 reproducible between seasons and were predictive of natural lodging observed in the wet season for  
24 a subset of 8 genotypes. Cultivars PARAO and CT 5805 from Latin America consistently stood out for  
25 superior lodging resistance. Across genotypes, morphological traits such as plant height, biomass or  
26 stem diameter were not or poorly predictive of lodging induced by Blaster. The best single proxy trait,  
27 stem-base bending moment at breakage (BM), explained about 40% of Blaster-induced lodging, and  
28 the Lodging Resistance Index composed of plant height, wet biomass and BM explained about 70%.  
29 We propose that Blaster is a reliable tool to evaluate crop lodging resistance as affected by genotype,  
30 cultural practices or season.

31 **Keywords:** *Oryza sativa* L., Lodging resistance, Wind channel, Stem morphology, Bending moment.

32

## 33 1. Introduction

34 Crop lodging is the physical collapse of the plant canopy which can happen spontaneously because of  
35 mechanical instability of the plant structure, through external forces such as wind, or both. Although  
36 the economic losses incurred by lodging are generally poorly documented for rice, there is consensus  
37 among breeders that lodging resistant varieties are needed. Lodging causes yield losses, according to  
38 one report (Setter et al., 1997) at field scale roughly equivalent to a 50% yield reduction applied to the  
39 fraction of the field area affected by lodging, as a combined result of reduced photosynthesis of the  
40 collapsed canopy, reduced grain recovery in mechanized harvesting systems, and pathogen complexes  
41 benefiting from high humidity in the collapsed canopy. Lang et al. (2012) observed similar yield  
42 reductions caused by mechanically forced lodging, associated with loss of grain quality.

43 The semidwarf “green revolution” varieties developed since the 1960s incorporated some lodging  
44 resistance, allowing the application of more fertilizer, which contributed to their success (Yoshida,  
45 1981). However, shifts in cultivation practice from transplanting to direct seeding, and new cultivars  
46 with a very high harvest index and biomass, brought back lodging risks. Lodging is now prevalent in  
47 high-input systems using high yielding cultivars (Ghanbari-Malidarreh et al., 2012) and under high  
48 planting density (Mobasser et al., 2009). Best-performing cultivars are frequently affected by lodging  
49 as they are top-heavy (Kashiwagi, 2014). Globally increasing on-farm yields over the past decades (Ray  
50 et al., 2013) and the greater yield potential of hybrid rice require renewed efforts to improve lodging  
51 resistance. Further increase in genetic yield potential will be ineffective without improved lodging  
52 resistance.

53 Rice lodging happens during grain filling and is associated with large shoot biomass especially panicles,  
54 canopy height, several environmental factors (such as pushing force by wind, wetting of canopy by  
55 rains, poor root anchorage caused by soft soil), crop management and nutritional factors such as high  
56 nitrogen fertilizer application (Shimono et al., 2007). According to a survey in China reported by Niu et  
57 al. (2016), strong wind alone caused 8%, strong rain 19% and the combination of both 23% of observed,  
58 natural lodging. The two factors in combination thus have synergistic effects. Other factors affect stem  
59 stability. Stems tend to be weak under close plant spacing (Mobasser et al., 2009), low silica availability  
60 (Idris et al., 1975), sheath blight attacks (Wu et al., 2012), or constitutively weak stems having long  
61 internodes and thin stem wall (Guangle et al., 2007). For wheat, stem anatomy was shown to affect  
62 lodging (Kelbert et al., 2004; Wang et al., 2006). Chemical composition of the stem such as cell wall  
63 lignin (Ookawa and Ishihara, 1993) and cellulose content (Kokubo et al., 1991) participate in crop  
64 mechanical stability and lodging resistance. Lodging may occur below the plant base when superficial  
65 parts of the root system are dislodged (root lodging), or by the bending or breaking of basal internodes  
66 of stems (stem lodging) (Berry et al., 2003). Although tall traditional cultivars tend to lodge easily, plant

67 height is not correlated with genotypic lodging resistance when it is inferior to 120 cm (Islam et al.,  
68 2007).

69 The lower parts of rice stems, which are exposed to the greatest bending force, are mechanically  
70 reinforced by several layers of leaf sheaths enclosing the basal internodes (Ookawa and Ishihara,  
71 1992). Sheaths progressively lose their mechanical stability during ripening due to terminal senescence  
72 (usually accelerated dense crop stands and the associated competition for resources) and  
73 opportunistic pathogens that invade moist, senescent tissue. Stay-green therefore contributes to  
74 lodging resistance (Kashiwagi et al., 2006; Ishimaru et al., 2008). In contrast to the whip-like, elastic  
75 upper parts of the stem (including the peduncle), the lower portion enclosed in sheaths is rigid. This  
76 rigidity is irreversibly lost once breakage has occurred. Lodging begins locally on a plot and spreads to  
77 larger surfaces through a mechanical domino effect.

78 Most studies on genetic control of lodging resistance were conducted in Japan (Murai et al., 2004;  
79 Sunohara et al., 2006; Kashiwagi et al., 2006; Ookawa et al., 2010; Jiang et al. 2018). Different methods  
80 were used to artificially induce lodging such as dragging a weighted plywood board on wheels through  
81 the field (Kelbert et al., 2004); exerting controlled sideways pressure on segments of the crop canopy  
82 (Caierão, 2006; adapted from Sisler and Olson (1951)); applying horizontal pulling force with a special  
83 pulley systems (Idris et al., 1975); and applying lateral pushing force to individual plants with a  
84 mechanical (Kashiwagi and Ishimaru, 2004) or electric prostrate tester (Niu et al., 2012). Mobile, truck-  
85 sized wind generators are used by a large maize seed company to test for lodging resistance (Dingkuhn,  
86 personal observation). Other studies depended on natural lodging conditions and visual scoring of  
87 lodging incidence (Futakuchi et al., 2008). Natural lodging can also be mapped from images visually  
88 (Ogden et al., 2002) or by extracting spectral and/or thermal signatures (Liu et al., 2018).

89 To phenotype genetic populations, identify parent materials and evaluate breeding products, a large  
90 number of genotypes need to be characterized based on a standard methodology capable of  
91 differentiating them. Recent studies identified molecular markers controlling lodging resistance (e.g.,  
92 Yano et al., 2014), mostly using proxy traits such as stem bending or breaking moment or stem or culm  
93 diameter (Zhu et al., 2016). However, it is difficult to relate those proxy traits to lodging resistance at  
94 field scale under natural conditions because the weather conditions triggering lodging cannot be  
95 controlled or predicted (Kelbert et al., 2004). Morphological or mechanical proxy traits are also not  
96 able to capture lodging resistance in its complexity, as it depends not only of stem stability but a host  
97 of other traits; and it depends not only on the force of wind but also wetting, presumably through its  
98 weight effect.

99 In this study, we therefore sought to develop and evaluate a mobile methodology called Blaster to  
100 induce controlled lodging at experimental plot level that would apply to the rice crop on a restricted

101 surface the rainstorm conditions that typically cause lodging. We furthermore sought to evaluate the  
102 method's repeatability; ability to discriminate among different rice genotypes under transplanted,  
103 flooded conditions; and the relationships between the extent of induced lodging with proxy traits  
104 frequently used for lodging resistance.

105

## 106 **2. Materials and Methods**

107 In 2013 wet season (WS), a rice-blaster was developed and successfully tested under field condition  
108 for the first time at IRRI, Los Baños, Philippines. The blaster was upgraded and has been in use since  
109 2014 dry season (DS), on the experimental fields of IRRI. Our Study comprised four field seasons (WS  
110 2013 WS, DS 2014, WS 2014, DS 2015).

### 111 **2.1 Rice-blaster**

112 The Blaster is an original development by the authors and was conceived in the context of a rice lodging  
113 research project (SKEP) involving the International Rice Research Institute (IRRI) in the Philippines, the  
114 Syngenta rice program in India and Cirad in France. It is a plot-scale mobile system which generates  
115 cyclone-like conditions within an open-air, 1 m wide and 6 m long wind channel (Fig. 1) blowing at a  
116 shallow angle into the rice canopy with a maximum wind speed of 60 km h<sup>-1</sup> at about 2-3 m from the  
117 turbine's outlet. The turbine is electric (Suiden Jet Fan Jumbo series SJF-700A-3, Japan) and mounted  
118 at an adjustable angle on a portable metal frame. The rice-blaster is equipped with four caster wheels  
119 with brakes to facilitate plot-to-plot movement (or alternatively, skids). A jet of water is injected into  
120 the wind stream with an adjustable nozzle. We used a submersible pump (Daichi S-1021P, Japan)  
121 drawing water from irrigation facilities (where not available, a mobile reservoir would be needed).  
122 Power was provided with a portable generator (Honda EG6500CXS, Japan). Although lodging extent  
123 was measured manually, we also mounted imagery system on the Blaster (GoPro HERO3+, USA) to  
124 monitor the lodging process, and also mounted three Non-Contact Ultrasonic Level Transmitter  
125 sensors (Omega LVU30, USA) linearly arranged 10 cm apart on a horizontal pole to monitor the  
126 dynamics of canopy height during blasting (Fig. 1). Ultrasonic sensors are connected to a monitor and  
127 control data logger (Campbell CR1000, USA).

128 The angle of the turbine was adjusted to 20° (descending) from the horizontal position to achieve  
129 maximal wind force hitting the canopy tops ca. 1.5 m from the blaster and enabling the wind stream  
130 to penetrate into the canopy. For this purpose, the height of the turbine was adjusted to a position  
131 slightly above canopy tops.

132 After field testing of Blaster in 2013 WS, a standard methodology was established to induce lodging.  
133 Blaster was operated sequentially at different wind speeds (30, 45, and 60 km h<sup>-1</sup>) at a constant

134 simulated rainfall (1.5 mm min<sup>-1</sup>). Canopy height was manually measured using a meter stick as  
135 described further down, (1) before blasting, (2) immediately after each wind speed treatment, (3) 15  
136 to 20 min after 60 km h<sup>-1</sup> blasting (immediate recovery), (4) 3 d after blasting (late recovery), and (5) 7  
137 d after blasting (late recovery). Duration of blasting varied with wind speed: 5 min at 30 km h<sup>-1</sup>, 4 min  
138 at 45 km h<sup>-1</sup> for, and 3 min at 60 km h<sup>-1</sup> (full speed blasting).

139 (Fig. 1 about here)

140 Lodging was calculated as percent decrease in canopy height from its initial upright position as shown  
141 in Eq. 1. Similarly, percentage recovered was calculated as the percent increase in canopy height from  
142 its lodged position as shown in Eq. 2.

143 **Equation 1**

$$Lodging (\%) = \frac{NL - L}{NL} * 100$$

144

145 *Whereby:*

146 NL, canopy height Non-Lodged [m]

147 L, canopy height Lodged [m]

148

149 **Equation 2**

$$Recovery (\%) = \frac{R - L}{NL - L} * 100$$

150

151 *Whereby:*

152 R, canopy height recovered after blasting [m] (where not stated otherwise, 7 d after blasting)

153 NL, canopy height Non-Lodged [m]

154 L, canopy height Lodged after blasting [m] (where not stated otherwise, blasting at 60 km h<sup>-1</sup>)

155

156 Figure 2 illustrates schematically the measurements used to calculate the extent of lodging and  
157 subsequent recovery. These measurements were performed on the central row of plants within the  
158 Blaster's air channel from 0.8 m to 2.4 m into the field (supplemental Fig. S1).

159 Blaster was used to induce lodging when 50% plants in a plot were at late dough grain stage (31-35%  
160 grain moisture content). In dry season experiments, all plots were subjected to Blaster treatment. In  
161 wet season experiments, only plots that did not lodge spontaneously due to the season's frequent  
162 rainstorms were subjected to induced lodging, whereas the other traits were measured in all plots.

163 (Fig. 2 about here)

## 164 **2.2 Load-testing device**

165 To measure the bending moment of excised stems at breaking point, a load-testing device was  
166 developed (supplemental Fig. S2). The device is equipped with a prostrate tester (DIK-7401, Daiki Rika  
167 Kogyo Co., Ltd., Japan) that exerts the vertical load on a specific region on the horizontally suspended  
168 stem. The basal internode region to be tested is placed between the two supporting points (fulcra) and  
169 the load is applied on the internode at the center between the two fulcra via around rubber bar of 12  
170 mm diameter. (A sharp edged wedge would bias the measurement by cutting into the tissue.) The  
171 distance between fulcra is adjustable. The load exerted on the internode is readable on the prostrate  
172 tester in mm units. The reading is then converted to load units (kg) depending on the strength of the  
173 spring used in the tester. The measurement consists of taking the reading of the maximal value  
174 observed while slowly descending the bar until the stem segment is broken to form a ca. 45° angle.

175 Measurements were done in the field to avoid turgor loss of excised stems during transport. We  
176 generally measured bending moment at breakage on complete main stems (composed of the culm  
177 and the leaf sheaths surrounding it cylindrically), at the height of either the 2<sup>nd</sup> or 3<sup>rd</sup> internode  
178 (counting from bottom).

179 Bending moment was only measured in the DS 2015 experiment. The distance between fulcra was  
180 adjusted to 5 cm. Bending moment at breaking (BM) was calculated as  $BM [kPa\ cm] = BL * D$ , whereby  
181 BL is the bending load (in kPa, equivalent to kg) and D is the distance between fulcra in cm.

## 182 **2.3 Proxy traits and index calculations to evaluate lodging resistance**

183 On the day of Blasting (dough stage, two wk after flowering, corresponding to about 35% grain  
184 moisture) for any given plot, key traits were observed on plants on portions of the plots that were  
185 unaffected by blasting (for plot design refer to supplemental Fig. S1). The traits were as follows:

### 186 *Stem morphology:*

187 Main stems from four arbitrarily selected hills on plot segments located beside the path of the wind  
188 channel (but excluding border rows) were dissected for each plot. Stem and culm diameter were  
189 observed with a digital Vernier caliper near the bottom of the plant (level of 2<sup>nd</sup> elongated  
190 internode). Since the cross section of rice stems sometimes as the shape of an ellipse, both the  
191 maximal and minimal width were measured and averaged. The culm was then isolated by removing  
192 the tubular leaf sheath layers and the measurement was repeated. The overall culm length and the  
193 length of the 2<sup>nd</sup> and 3<sup>rd</sup> internodes were also measured.

194 *Stem bending moment:*

195 Main stems from three arbitrarily selected hills on plot segments located beside the path of the wind  
196 channel (but excluding border rows) were dissected for each plot. Bending moment at breakage was  
197 measured at the height of the 2<sup>nd</sup> elongated internode as described above.

198 *Lodging resistance index:*

199 Lodging resistance index (LRI) was calculated for the crop around the time of blasting according to  
200 (Ookawa and Ishihara, 1992) using Equation 3. It expresses the ratio of BM<sub>i</sub> (expressing the force  
201 needed to break the stem) over the whole-plant bending moment, or fresh-weight based lever, which  
202 in turn is equal to the product of the mean culm length and the fresh weight of the crop above the  
203 internode(i). BM<sub>i</sub> was measured for the 2<sup>nd</sup> and 3<sup>rd</sup> elongated internode (counting from bottom). We  
204 used the BM<sub>2</sub> in our calculations, which gave very similar results as for BM<sub>3</sub> (data not shown).

205 Crop fresh weight was observed for 3 entire hills per plot (20 cm x 60 cm ground area) on the day of  
206 blasting (but outside the path of the air channel). Plants were uprooted, the root system removed, and  
207 the aboveground portion weighed in a nearby facility. During transport the samples were kept in plastic  
208 bags in the dark to prevent moisture loss.

209 **Equation 3**

$$\text{LRI} = \frac{\text{BM}_i}{\text{FW} * \text{CL}}$$

211 *Whereby:*

212 LRI, Lodging Resistance Index

213 BM<sub>i</sub>, Bending Moment at internode(i) [kg cm]

214 FW, Fresh Weight per plant (above-ground parts) [kg]

215 CL, Culm Length (ground level to neck node) [cm]

216

217 *Crop yield at maturity:*

218 Grain yield was determined from a 5 m<sup>2</sup> on each plot in areas unaffected by the wind  
219 channel of the Blaster (Fig. S1). Aboveground dry weight and harvest index at maturity were  
220 determined for 12 hills adjacent to the grain yield area after drying of samples in ovens (60  
221 °C until constant weight).

222 **2.4 Field characteristics, experimental design and crop management for Blaster experiments**

223 Experiments were conducted on K4 block of IRRI experiment station, Los Baños, Philippines (14°11' N,  
224 121°15' E, 21m asl). Genotypes were arranged in a randomized complete block design (RCBD) with 4  
225 replications. Individual plot size was 4.8 m x 5.8 m (27.84 m<sup>2</sup>). The plots had a long-term history of rice  
226 monoculture (2 crops/year) with complete irrigation (flooding) and the soil was reasonably deep for  
227 irrigated rice (plow pan at ca. 30-40 cm). Fourteen-day old seedlings were transplanted from a seedbed  
228 nursery to the main field at the rate of one plant per hill. Hill to hill spacing was 20 cm x 20 cm (25 hills  
229 m<sup>-2</sup>).

230 Plants received a total N 90 kg ha<sup>-1</sup> in the WS applied in 3 splits and 200 kg ha<sup>-1</sup> in the DS applied in 4  
231 splits as urea. Other fertilizers applied were P, K and Zn at 30(15), 40(20) and 5(2.5) kg ha<sup>-1</sup>, respectively  
232 in DS (values for WS in brackets). Irrigation was started from 7-10 days after transplanting until panicle  
233 initiation and water was maintained at 3-5 cm deep. Standing water was maintained from flowering  
234 to one week before harvest and drained thereafter. Standard cultural management practices were  
235 followed. Prophylactic measures against sheath blight and stem borers were done.

236 Sowing was performed on 11 June 2013 (WS 2013), 04 December 2013 (DS 2014), 18 June 2014 (WS  
237 2014) and 08 January 2015 (DS 2015).

### 238 ***2.5 Validation experiment in wet season***

239 A subset of 8 genotypes was taken from the panel to conduct a validation experiment on natural  
240 lodging in the wet season. The subset selection did not reflect observed response to Blaster because  
241 validation trials were initiated before the Blaster was operational, and it reflected diversity only based  
242 on breeders' observations in MET trials. The 8 genotypes were V1, V9, V12, V13, V14, V16, V17 and  
243 V20 (Table 1).

244 Seed was sown (transplanted) on 12 June (26 June), 22 June (6 July) and 2 July (16 July) in the 2013  
245 wet season; and on 4 June (18 June), 18 June (2 July) and 2 July (16 July) in the 2014 wet season on the  
246 same field where the dry-season Blaster experiments were conducted. Plant spacing and water  
247 management were the same as in the dry season experiments. Each experiment had a randomized  
248 complete block design with 4 replications, with elemental plots measuring 4m X 6m. Fertilizer  
249 application was 15, 20 and 2.5 kg ha<sup>-1</sup> P/K/Zn basal and 120 kg ha<sup>-1</sup> N as urea as triple split in equal  
250 proportions at transplanting, maximum tillering and panicle initiation stages. The N fertilizer rate was  
251 above recommended rate for the wet season in order to increase lodging probability. Lodging  
252 incidence was estimated as % plot area lodged at grain maturity. For the purpose of blaster validation,  
253 mean genotypic lodging incidence across all 6 environments was used. The sowing dates thereby  
254 served to increase the probability for rainstorms to affect all genotypes despite phenological

255 differences. This validation trial will be reported in more detail elsewhere in the context of modeling  
256 of rice lodging.

## 257 **2.6 Genetic materials**

258 Twenty rice genotypes (Table 1) were studied. All accessions were indica types except Parao (V18), a  
259 tropical japonica variety. The panel was composed to include a majority of high yielding cultivars and  
260 advanced breeding lines (from breeders' replicated and multi-environment trials (MET)), as well as a  
261 smaller number of tall and medium tall lines. Emphasis was given, as far a prior information was  
262 available, on contrasting stem thickness, internode length, phyllochron and pushing resistance in the  
263 field (data not presented), as well as breeders' field observations on lodging in MET. Seed was obtained  
264 from IRRI's germplasm bank or directly from breeders. In contrast to temperate japonica rices that are  
265 well studied for lodging particularly in Japan, there are to our knowledge no established resistance  
266 checks for tropical indica rice. However, Ookawa et al. (2010) reported superior stem BM for the indica  
267 cultivar Habataki in Japan, which was included in our panel. NSIC Rc222 (V2) is a local check.

268 (Table 1 about here)

## 269 **2.7 Data analysis and graphical presentation**

270 All Figures were plotted and linear regression lines drawn using SigmaPlot for Windows Version 12.5  
271 (Systat Software, Inc.) Standard error (SE) for each genotype was calculated in Excel sheet (Microsoft  
272 Office Excel 2007). Statistical Tools for Agricultural Research (STAR) Version 2.0.1 (IRRI) was used for  
273 ANOVA and the calculation of broadsense heritability ( $H^2$ ).

274

## 275 **3. Results**

### 276 **3.1 Dynamics of crop lodging upon Blaster application**

277 The Pic. S1 illustrates how Blaster affected the rice canopy. Canopy height at the center of the wind  
278 channel was used to evaluate lodging dynamics before and after induced lodging (Fig. 3AB: only crops  
279 that did not spontaneously lodge *before* induced lodging are shown). Canopy height at standing  
280 position before blasting ranged from 0.7 to 1.5 m in dry season (DS) depending on genotype (Fig. 3A).  
281 Canopy height decreased gradually (lodging) as wind speed was increased in three steps from 30 to 60  
282  $\text{km h}^{-1}$ . After blasting at 60  $\text{km h}^{-1}$ , canopy height was reduced to between 0.1 and 0.5 m. Greater  
283 lodging was observed in DS 2015 than in DS 2014 in terms of reduction in canopy height at the same  
284 wind speed.

285 A slight recovery of canopy height was observed 15 min after blasting and a stronger one 3 d later.  
286 From 3d to 7d after blasting, no further recovery was observed. In wet season (WS) (Fig. 3B), trends  
287 were similar as in DS but less genotypes could be observed because most accessions lodged  
288 spontaneously even before blasting due to rainy and windy weather. Due to the sparse WS data, we  
289 focus in the following on DS data.

290 Among genotypes in DS (Fig. 3A, Table 2), CT 5805 (V10) and PARAO (V18) stood out by lodging  
291 comparatively little. Both accessions also stood out in the WS (Fig. 3B). HABATAKI (V11) and IR10N225  
292 (V17) lodged little in DS 2014 but more in DS 2015. V17 was also among the accessions that did not  
293 lodge spontaneously in the WS whereas V11 did.

294 Across genotypes and years, the recovery from lodging seven days after blasting was negatively  
295 correlated ( $R^2=0.74$ ,  $P<0.001$ ) with the lodging observed immediately after blasting at  $60 \text{ km h}^{-1}$  in the  
296 DS (Fig. 3 C). Plots that lodged severely (>75% reduction of canopy height) did not recover at all,  
297 whereas plots that lodged moderately (40-50% reduction of canopy height) recovered 60-80% of the  
298 loss in canopy height. Consequently, the moderate, largely reversible lodging fell within the range of  
299 mechanical elasticity, whereby the recovery did not happen within the initial 15 min but was  
300 accomplished within 3 d (Fig. 3A). However, lodging causing >75% reduction in canopy height in DS  
301 had no elasticity component (Fig. 3C). The elasticity component (recoverable lodging) appeared to be  
302 smaller in WS but data was too sparse to ascertain it (Fig. 3D).

303 (Fig. 3 about here)

### 304 **3.2 Relationship between Blaster response and lodging-related crop traits**

305 Among all the crop traits measured, the 2<sup>nd</sup>-internode stem bending moment at breakage ( $BM_2$ )  
306 using the device shown in supplemental Fig. S1 was the most predictive of actual lodging as induced  
307 by Blaster. Correlations between induced lodging at three wind speeds and  $BM_2$  are shown for DS-  
308 2015 in Fig. 4 ABC. Across all genotypes that did not lodge spontaneously,  $BM_2$  explained between 39  
309 and 44% of lodging depending on wind speed ( $P<0.01$ ). When cases of spontaneous lodging were  
310 included,  $R^2$  values increased to between 0.40 and 0.60. (Their inclusion is legitimate when genotypic  
311 lodging resistance is compared, but not when Blaster is evaluated.) The  $BM_2$ , in turn, could be  
312 partially explained with stem morphology (supplemental Fig. S3). Stem diameter explained 32% of  
313 variation in  $BM_2$ , sheath thickness explained 20% and culm diameter only 4%.

314 (Fig. 4 about here)

315

316 Compared to BM<sub>2</sub>, morphological traits such as stem diameter were less predictive of induced  
317 lodging with genotypes excluded that lodged spontaneously (Table S1). Plant height and culm length  
318 (from base to neck node) had R values around +0.5 (R<sup>2</sup> of 0.25) and were mostly significant (P<0.05).  
319 Stem mean diameter at the 2<sup>nd</sup> internode had similar R values but they were negative, whereby the  
320 minor and major diameter had similar effects (only mean diameter presented in Table S2). Of the  
321 two component traits of stem diameter, the thickness of the sheath layer around the culm accounted  
322 for the correlation whereas culm diameter had no effect. Panicle number per hill, aboveground dry  
323 weight and grain yield had much lower correlations than plant height and stem thickness related  
324 traits.

325 The best predictions of observed lodging after Blaster treatment were achieved with a combination  
326 of three independently measured traits constituting the Lodging Resistance Index (LRI, Eq. 3). The LRI  
327 is a simple mechanistic model that assumes lodging resistance to be proportional to BM and  
328 inversely proportional to the gravitational lever (canopy height X wet weight). The LRI was negatively  
329 correlated with Blaster-induced lodging (Fig. 4 DEF) and explained 65%, 73% and 72% of genotypic  
330 variation of Blaster response at 30, 45 and 60 km h<sup>-1</sup> wind speed, respectively. With the inclusion of  
331 spontaneous lodging cases, R<sup>2</sup> was 75%, 75% and 68%.

332 The varieties PARAO (V18) and CT 5805 (V10), which were also the most lodging resistant in DS 2014  
333 (Table 2), had the greatest LRI and lowest lodging percentage in DS 2015 at all wind speeds (Fig. 4). At  
334 the higher wind speeds (45 and 60 km h<sup>-1</sup>), cv. HABATAKI (V11) also had a superior LRI but did not stand  
335 out in terms of induced lodging. Similarly, IR07A179 (V13) suffered greater induced lodging than would  
336 be expected from its LRI value, indicating that individual genotypes may have high LRI but lodge despite  
337 it. The lowest LRI was observed for genotypes V3 (CO 18), V5 (VELLAI SEENETTI) and V9  
338 (HONDERAWALA) (data not presented), and these genotypes lodged spontaneously soon after  
339 flowering and before blaster treatment, despite the absence of strong natural wind or rainfall (Table  
340 2).

### 341 **3.3 Repeatability of genotypic responses to Blaster**

342 Genotypic response to Blaster treatment at 30 km h<sup>-1</sup> wind speed was similar between DS 2014 and  
343 DS 2015 across genotypes, although lodging was more severe in DS 2015 than in DS 2014 as indicated  
344 by the intercept (Fig. 5). At 45 km h<sup>-1</sup> and 60 km h<sup>-1</sup>, the difference between years increased whereby  
345 the correlation remained highly significant. Consequently, the blasting methodology to induce  
346 lodging was repeatable between years in terms of varietal differences but the absolute extent of  
347 lodging varied strongly between years.

348 (Fig. 5 about here)

349 According to ANOVA (box in Table 2), block effects were not significant. Year effects were not  
350 significant at 30 km h<sup>-1</sup> blasting but highly significant (P<0.01) at higher wind speeds. Genotype  
351 effects and genotype x year interactions were highly significant (P<0.0001) for all wind speeds. The  
352 factor interaction was in large part due to V17 which lodged little in 2014 and much in 2015 (Table 2).  
353 The mean coefficient of variance was highest at 30 km h<sup>-1</sup> and decrease at higher wind speeds.  
354 Genotypic seasonal means ( $\pm$ SE) are presented in Table 2 and show that V10 and V18 stood out  
355 consistently in terms of lower lodging.

356 (Table 2 about here)

357 The broadsense heritability (H<sup>2</sup>) of genotypic lodging response was high within a given year (with  
358 only block effects contributing to non-genotypic sources of variance), particularly at high wind  
359 speeds at blasting (H<sup>2</sup>>0.9 in 2015) (Table 2). However, across years, H<sup>2</sup> was low due to strong  
360 interannual differences in the lodging response.

361 (Table 3 about here)

### 362 ***3.4 Potential causes of different lodging response in DS 2014 and DS 2015***

363 The DS 2014 crop was sown on 04 DEC 2013 whereas the DS 2015 crop was sown 35 d later in the  
364 season, on 08 JAN 2015. This was associated with marked differences in crop characteristics as  
365 summarized in Fig. S4. In terms of phenology, the DS 2015 crop flowered on average a week later  
366 than the 2014 crop (between -1 d and +8 d, depending on genotype) (Fig. S4A). The DS 2015 crop  
367 was slightly taller (Fig. S4B) and tillered more as indicated by greater panicle number (Fig. S4E).  
368 Aboveground dry weight at maturity (Fig. S4C) and grain yield (Fig. S4D) were similar between years  
369 for the lesser-yielding genotypes, but greater in DS 2015 for the higher-yielding ones.

370 These inter-annual differences were associated with different stem morphology, the heavier DS 2015  
371 crop having a lower stem diameter at its base (level of 2<sup>nd</sup> elongated internode) (Fig. S4F), which was  
372 in turn mainly due to a much thinner layer of leaf sheaths surrounding the culm (Fig. S4H), whereas  
373 the culm-internode diameter varied less between years (Fig. S4G).

374 Consequently, the DS 2015 crop was on average taller, heavier and had thinner stems. Each of these  
375 traits can be expected to increase lodging incidence, and indeed the extent of lodging induced by  
376 blaster was greater in 2015 (Fig. 5). Supplemental Fig. S5 shows that the difference lodging between  
377 the years was positively correlated with the difference in grain yield between years (P<0.01).

378 We did not further analyze how the difference in sowing date between the years caused the  
379 phenological and morphological differences. Climatic conditions were similar between 2014 and

380 2015, but the much earlier sowing date in DS 2014 caused crop exposure to lower early-season  
381 temperatures (Supplemental Fig. S6).

### 382 **3.5 Validation of Blaster with natural lodging**

383 A subset of 8 genotypes was subjected to natural lodging during the generally more lodging-prone  
384 wet season using 6 environments (3 sowing dates x 2 years). This subset did not represent the  
385 greatest genotypic differences in lodging resistance within the larger panel because the natural-  
386 lodging experiment was initiated before the blasting experiments. The mean genotypic, natural  
387 lodging incidence in the subset (in terms of % plot area lodged at maturity) was plotted against  
388 lodging intensity caused by blaster (% canopy height reduction) in the 2014 and 2015 dry seasons  
389 (Fig. 6). Cross-environment means of natural lodging were used here because the different genotypic  
390 phenology and the unpredictable weather would make single-environment lodging data quite  
391 meaningless for genotypic comparisons.

392 (Fig. 6 about here)

393 The strongest correlations were observed for blasting at 30 km h<sup>-1</sup>, whereby correlations were better  
394 for 2015 blasting ( $R^2=0.82$ ,  $P=0.002$ ) than for 2014 ( $R^2=0.54$ ,  $P=0.038$ ). The 2015 blasting response at  
395 45 km h<sup>-1</sup> was also highly significantly correlated with natural lodging ( $P=0.005$ ). However,  
396 correlations declined at higher Blaster wind speeds. For both years and all for Blaster wind speeds,  
397 the least lodging genotype after blasting (V17) also showed the least natural lodging, and the most  
398 lodging genotype after blasting showed the most natural lodging in the wet season. When two-year  
399 means of blasting results were compared with two-year means of natural lodging (data not  
400 presented), correlations had  $R^2=0.70$  ( $P=0.0097^{**}$ ),  $R^2=0.55$  ( $P=0.035^*$ ) and  $R^2=0.42$  ( $P=0.081$ n.s.) for  
401 blasting at 30, 45 and 60 km h<sup>-1</sup>, respectively. Overall, induced lodging by Blaster in 2015 dry season  
402 was highly predictive of natural lodging in wet season, but induced lodging in 2014 was less  
403 predictive for unknown reasons.

### 404 **3.7 Lodging resistance vs. grain yield**

405 Across genotypes, lodging (either induced at 30 km h<sup>-1</sup> wind speed or spontaneous, in which case  
406 Blaster was not applied) showed a strong correlation with grain yield observed at maturity on the  
407 plot sector not subjected to Blaster (Fig. 7A). The relationship was curvilinear and results were similar  
408 for the other wind speeds (data not presented). Greatest yields were observed for genotypes that  
409 lodged moderately. The low yields observed for genotypes that lodged the most were associated  
410 with tall plant type (Fig. 8B). However, among the 11 genotypes that yielded 7.5 Mt ha<sup>-1</sup>) or more,  
411 which were all short statured (up to 120 cm), a wide range of lodging responses was observed (from

412 <20% to >50%). Consequently, within the yield and plant height ranges targeted by breeders,  
413 substantial diversity in lodging resistance was observed.

414 (Fig. 7 about here)

415

## 416 **4. Discussion**

### 417 ***4.1 Advantages and limitations of Blaster methodology***

418 The new Blaster methodology is a tool to measure the lodging resistance of a crop at the plot (plant  
419 population) scale, thereby exposing the plants to the weather factors that commonly cause lodging  
420 (combination of wind force and wetting: Niu et al., 2016) in a controlled and reproducible fashion.  
421 Does the Blaster accurately reproduce natural rainstorm conditions commonly causing lodging? It  
422 certainly does reproduce the domino effect as heavy, wetted plants exposed to the wind vector lean  
423 on their neighbors. The wind speed generated at the canopy top (up to 60 km h<sup>-1</sup> or about 17 m s<sup>-1</sup>)  
424 may not appear as extreme, but it is equivalent to substantially higher wind speeds measured at 2m  
425 at a weather station that is free of crop canopies acting as wind brakes.

426 Naturally occurring wind gusts in the field also form eddies (Dupont et al., 2010) that expose the crop  
427 to changing wind directions and velocities. Migrating eddies are probably responsible for the “snaking”  
428 lodging paths frequently observed in the field (Dingkuhn, personal observation), causing spatially  
429 heterogenous lodging distribution. The Blaster method does not reproduce these complex  
430 phenomena, which is also in the interest of repeatability. On the other hand, the critical wind speed  
431 causing lodging by Blaster cannot be easily used to predict lodging on the basis of standard weather  
432 station data.

433 The extent of lodging generated by Blaster is a result of the numerous phenotypic traits participating  
434 in lodging resistance (e.g., plant height, leaf area, wet biomass, stem stiffness and elasticity), the crop’s  
435 mostly unknown aerodynamic resistance (Liu et al. 2006), and the crop’s anchorage in the soil which  
436 in turn depends on the soil type and condition and the planting method (e.g., transplanting vs. direct  
437 seeding in the case of rice). The method thus quantifies lodging resistance in terms of an emergent  
438 property of a complex, multi-factorial system. This is in marked contrast with the most commonly used  
439 proxy traits for lodging resistance, mostly applying mechanical force to one or many stems (Kashiwagi  
440 and Ishimaru, 2004; Kelbert et al., 2004; Caierão, 2006; Niu et al., 2012) or measuring one or several  
441 morphological traits (e.g., height, weight, stem diameter, internode length). Since these proxies are  
442 component traits of a complex system, their individual contribution to lodging resistance is bound to  
443 vary in an unknown way. In fact, if Blaster methodology is combined with the measurement of

444 component traits, as attempted here, their contribution to lodging resistance can be quantified within  
445 the specific environmental and agronomic context of the experiment.

446 From a practical point of view, the Blaster method is rapid enough (5-10 min per measurement, plus  
447 the time to move to the next plot) to measure lodging resistance on large agronomic experiments, but  
448 too time consuming to be applied to genetic phenotyping trials which have 100s to 1000s of plots. The  
449 method also has substantial space requirements, as the 1-m wide wind channel calls for a plot width  
450 of  $\geq 1.5\text{m}$  and depth of  $\geq 6\text{m}$ . Furthermore, a trafficable field border is needed on which to move the  
451 equipment. These requirements can be easily met for agronomic experiments and the evaluation of  
452 advanced breeding materials, but may be prohibitive for phenotyping or varietal screening objectives.  
453 Likewise, the destructive nature of the measurement may not be compatible with all experimental  
454 designs.

455 Although we did not test it, the Blaster method is not restricted to rice. It should work equally well for  
456 other short-statured ( $< 1.5\text{m}$ ) cereals such as wheat or barley, whereas the wind channel would be  
457 under-dimensioned for tall grasses such as tall-traditional or biomass sorghums or millets. Likewise,  
458 Blaster should theoretically be equally suited study stem lodging (e.g., transplanted rice) or root  
459 lodging (direct-seeded rice or wheat), although the components traits and the effect of lodging on yield  
460 may be different.

461 The fact that the Blaster is positioned outside the planted plot for measurements, thereby facing  
462 border plants, is probably not a source of bias. According to our measurements, plants located up to  
463 2m into the plot experience about the same wind speed and wetting as do border plants, and the  
464 border plants were not included in our measurements of lodging. The reproducibility of induced  
465 lodging by blaster between years, in terms of genotypic differences was good (73% at  $30\text{ km h}^{-1}$ )  
466 despite large differences in biomass, yield and number of fertile tillers between years. The high  
467 significance of genotypic differences in lodging within a year ( $P < 0.001$ ) also indicates good  
468 repeatability. We thus consider the method mature for broader application.

#### 469 ***4.2 Repeatability***

470 Within a season, the repeatability of genotypic Blaster response was very high as indicated by  $H^2$  values  
471 around 0.9 at higher wind speeds. However  $H^2$  across 2014 and 2015 experiments was low, a result of  
472 smaller lodging response to Blaster in 2014, which in turn can be explained by a much thicker layer of  
473 leaf sheaths attached to the culm (giving the stem more strength), combined with smaller fertile tiller  
474 number and smaller crop biomass in 2014. In fact, the sowing date for 2014 was unusually early for  
475 the season (caused by forced farm occupation plans) which exposed the tillering and panicle initiation  
476 phase to low temperatures. It is therefore not surprising that Blaster results in 2015 dry season were

477 highly predictive of natural lodging in the wet season (which is not affected by low temperatures),  
478 whereas 2014 Blaster results were not.

479 The observed high correlation of 2015 induced lodging (dry season) with natural lodging (mean for  
480 2013 and 2014 wet seasons) is a crucial result because in the tropics, rice lodging is mainly a wet season  
481 problem. However, Blaster applications in the wet season are impractical because crops tend to lodge  
482 spontaneously but unpredictably. The results show that – at least in the Philippines and for the  
483 recommended sowing dates – induced lodging by Blaster in the dry season is predictive of natural  
484 lodging in the wet season. This should be validated for a larger range of environments and cultural  
485 practices.

#### 486 ***4.3 Relationship of Blaster-induced lodging with proxy traits for lodging resistance***

487 Among the component traits measured in our study, the 2<sup>nd</sup> internode bending moment at breakage  
488 explained 60% of observed variation in lodging after blasting at 30 km h<sup>-1</sup>. Plant height, biomass or stem  
489 diameter were poorly predictive of lodging. Mechanical strength of the stem is known to be crucial for  
490 lodging resistance. It is influenced by morphological (Guangle et al., 2007; Okuno et al., 2014),  
491 anatomical (Ookawa et al., 2010) and biochemical (Matsuyama et al., 2014; Peng et al., 2014) stem  
492 traits. In our study, Stem diameter was positively correlated with bending moment ( $P < 0.05$ ). Culm  
493 internode diameter and sheath thickness showed a similar trend but correlations were not significant  
494 (supplemental Fig. S4).

495 The Lodging Resistance Index (LRI) integrates three component traits, thus representing a simple  
496 model. It is proportional to the stem bending moment at breakage of the basal internode and inversely  
497 proportional to the gravitational lever, represented by the product of crop height and weight (Ookawa  
498 and Ishihara, 1992; Quang Duy et al., 2004). Islam et al. (2007) reported that the reciprocal of LRI,  
499 called lodging index, is correlated with visual lodging score observed in the field. Depending on the  
500 sample of varieties studied, different component traits may determine variation in LRI, such as plant  
501 height (Yanling et al., 2008) or stem bending moment (Zhang et al., 2014). In our study, LRI explained  
502 about 75% of Blaster-induced lodging at 30 and 45 km h<sup>-1</sup> wind speed, and slightly less at 60 km h<sup>-1</sup>. It  
503 can be expected that this correlation will substantially deteriorate when rice is direct seeded, which  
504 favors root lodging. (Root lodging is rare in transplanted rice because the shoot base is forced into the  
505 soil during transplanting.) LRI would have limited validity whenever root lodging occurs because it does  
506 not involve stem breakage, whereas the Blaster methodology can be expected to provide a valid  
507 estimate of a given crop's lodging resistance regardless of the type of lodging encountered. Further  
508 research is needed to confirm this.

509 After using the Blaster to induce lodging, it was possible to monitor recovery from lodging. The degree  
510 of recovery was generally limited and did not occur at all when lodging was complete (in the sense that  
511 the stems formed a tight horizontal mat). No angular compensatory growth was observed on culm  
512 nodes, and we assume that the limited recovery observed after moderate lodging, which was  
513 completed within 3d and did not continue thereafter, was a result of elasticity and was not a growth  
514 phenomenon.

#### 515 ***4.4 Genotypic differences in lodging resistance***

516 To our knowledge, no standard lodging resistance check cultivars are available for tropical rice  
517 (generally indica types), contrary to temperate, japonica-type rices that are well studied in Japan. We  
518 thus relied on breeders' experience (notably from multi-environment trials) and morphological criteria  
519 such as stem thickness to compose the diverse panel of 20 cultivars.

520 Within the limited genetic diversity represented by the panel, a large range of lodging responses was  
521 observed. The most lodging susceptible materials were moderately tall or tall, and not of the plant  
522 type breeders are looking for today. However, among the semidwarf materials, and specifically among  
523 the high yielding ones in our study, a large diversity of lodging responses was observed. Our sample  
524 was too small to conclude on yield vs. lodging resistance trade-offs, but the data do demonstrate that  
525 high lodging resistance can occur in high yielding varieties. Interestingly, the two most lodging resistant  
526 cultivars, CT 5805 and PARAO, are both from South America where they were bred for direct-seeded,  
527 high-input systems (C. Rebolledo, CIAT, pers. comm.) which are known to be prone to lodging.

#### 528 ***4.5 Potential applications of Blaster in crop improvement***

529 Although the Blaster method may not be suited to mass screening and phenotyping purposes, it can  
530 be used to evaluate the lodging resistance of advanced selections and of varieties before they are  
531 released. It can also be used, in conjunction with measurements of component traits, to identify the  
532 traits that contribute most to lodging resistance in a targeted environmental and agronomic setting,  
533 potentially rendering subsequent parent and progeny screening more effective. Dingkuhn et al. (2015)  
534 pointed out that particularly for tropical dry season crops, which receive abundant solar radiation,  
535 breeding for improved yield potential has been hampered by the concern to avoid excessive nitrogen  
536 resources and biomass production because they cause lodging. In fact, rice breeders in the tropics  
537 should more systematically select under conditions causing lodging, and also breed explicitly for  
538 lodging resistance. In Japan this is already the case.

#### 539 ***4.6 Potential applications of Blaster in agronomy***

540 It is known that high nitrogen inputs (Shimono et al., 2007), close plant spacing particular in  
541 conjunction with direct seeding (De Datta, 1986), and low-radiation wet-season conditions (in fact,

542 75% of our test varieties lodged spontaneously before Blaster treatment in WS) favor lodging. Different  
543 genotypes may respond differently to these conditions. The Blaster method is suited to produce  
544 meaningful data on lodging response for multi-factorial agronomic experiments, (e.g., fertilizer inputs,  
545 crop establishment practices, cultivar). This also opens up opportunities to develop crop models  
546 capable of predicting lodging as a function of crop traits and their interactions with management and  
547 environment, which do not exist at present.

548

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553

#### 554 **References:**

555 Berry, P.M., Sterling, M., Baker, C.J., Spink, L., Sparkes, D.L., 2003. A calibrated model of wheat lodging  
556 compared with field measurements. *Agric. Forest Meteorol.* 119, 167-180.

557 Caierão, E., 2006. Effect of induced lodging on grain yield and quality of brewing barley. *Crop Breeding  
558 and Applied Biotechnology* 6, 215-221.

559 De Datta, S.K., 1986. Technology development and the spread of direct-seeded flooded rice in  
560 Southeast Asia. *Exp. Agric.* 22, 417-426. <https://doi.org/10.1017/S0014479700014666>

561 Dingkuhn, M., Laza, M.R.C., Kumar, U., Mendez, K.S., Collard, B., Jagadish, K.S.V., Kumar, A., Singh, R.K.,  
562 Padolina, T., Malabayabas, M., Torres, E., Rebolledo, M.C., Manneh, B., Sow, A., 2015.  
563 Improving yield potential of tropical rice: Achieved levels and perspectives through improved  
564 ideotypes. *Field Crops Res.* 182, 43-59.

565 Dupont, S., Gosselin, F., Py, C., Hemon, P., Brunet, Y., 2010. Modelling waving crops using large-eddy  
566 simulation: comparison with experiments and a linear stability analysis. *J. Fluid Mech.* 652, 5–  
567 44.

568 Futakuchi, K., Fofana, M., Siè, M., 2008. Varietal differences in lodging resistance of African rice (*Oryza  
569 glaberrima* Steud.). *Asian Journal of Plant Sciences* 7, 569-573.

570 Ghanbari-malidarreh, A., Habibi, E., Mobasser, H., 2012. Response morphological traits related-lodging  
571 of rice (*Oryza sativa* L.) to chlormequat chloride application time and nitrogen rates in the  
572 north of Iran. International Conference on Agriculture, Chemical and Environmental Sciences.  
573 ICACES'2012, Dubai, UAE, pp. 6-7.

574 Guangle, S., Yingyao, S., Yanling, H., Yangjuan, S., Weigang, W., Conghe, Z., Duopu, C., 2007. Study on  
575 rice lodging resistance character and correlation between the culm traits and lodging  
576 resistance traits. *Chinese Agricultural Science Bulletin* 23, 58-62.

577 Idris, M., Hossain, M.M., Choudhury, F.A., 1975. The effect of silicon on lodging of rice in presence of  
578 added nitrogen. *Plant Soil* 43, 691-695.

579 Ishimaru, K., Togawa, E., Ookawa, T., Kashiwagi, T., Madoka, Y., Hirotsu, N., 2008. New target for rice  
580 lodging resistance and its effect in a typhoon. *Planta* 227, 601-609.

581 Islam, M.S., Peng, S., Visperas, R.M., Ereful, N., Bhuiya, M.S.U., Julfiquar, A.W., 2007. Lodging-related  
582 morphological traits of hybrid rice in a tropical irrigated ecosystem. *Field Crops Res.* 101, 240-  
583 248.

584 Jiang, M., Yamamoto, E., Yamamoto, T., Matsubara, K., Kato, H., Adachi, S., Nomura, T., Kamahora, E.,  
585 Ma, J., Ookawa, T., 2018. Mapping of QTLs associated with lodging resistance in rice (*Oryza*  
586 *sativa* L.) using the recombinant inbred lines derived from two high yielding cultivars,  
587 Tachisugata and Hokuriku 193. *Plant Growth Regul.*, [https://doi.org/10.1007/s10725-018-](https://doi.org/10.1007/s10725-018-0468-3)  
588 0468-3

589 Kashiwagi, T., 2014. Identification of quantitative traits loci for resistance to bending-type lodging in  
590 rice (*Oryza sativa* L.). *Euphytica* 198, 353-367.

591 Kashiwagi, T., Ishimaru, K., 2004. Identification and functional analysis of a locus for improvement of  
592 lodging resistance in rice. *Plant Physiol.* 134, 676-683.

593 Kashiwagi, T., Madoka, Y., Hirotsu, N., Ishimaru, K., 2006. Locus prl5 improves lodging resistance of rice  
594 by delaying senescence and increasing carbohydrate reaccumulation. *Plant Physiology and*  
595 *Biochemistry* 44, 152-157.

596 Kelbert, A.J., Spaner, D., Briggs, K.G., King, J.R., 2004. The association of culm anatomy with lodging  
597 susceptibility in modern spring wheat genotypes. *Euphytica* 136, 211-221.

598 Kokubo, A., Sakurai, N., Kuraishi, S., Takeda, K., 1991. Culm brittleness of barley (*Hordeum vulgare* L.)  
599 mutants is caused by smaller number of cellulose molecules in cell wall. *Plant Physiol.* 97, 509-  
600 514.

601 Lang, Y.-z., Yang, X.-d., Wang, M.-e., Zhu, Q.-s., 2012. Effects of Lodging at Different Filling Stages on  
602 Rice Yield and Grain Quality. *Rice Sci.* 19, 315-319

603 Liu S, Mao D, Lu L. 2006. Measurement and estimation of the aerodynamic resistance. *Hydrol. Earth*  
604 *Syst. Sci. Discuss.* 3, 681–705.

605 Liu, T., Li, R., Zhong, X., Jiang, M., Jin, X., Zhou, P., Liu, S., Sun, C., Guo, W., 2018. Estimates of rice  
606 lodging using indices derived from UAV visible and thermal infrared images. *Agric. Forest*  
607 *Meteorol.* 252, 144–154.

608 Matsuyama, H., Shimazaki, Y., Ohshita, Y., Watanabe, Y., 2014. Varietal difference in lodging resistance  
609 and culm characteristics of wheat. *Jpn. J. Crop Sci.* 83, 136-142.

610 Mobasser, H.R., Yadi, R., Azizi, M., Ghanbari, A.M., Samdaliri, M., 2009. Effect of density on  
611 morphological characteristics related-lodging on yield and yield components in varieties rice  
612 (*Oryza sativa* L.) in Iran. *American-Eurasian Journal of Agricultural and Environmental Science*  
613 5, 745-754.

614 Murai, M., Komazaki, T., Sato, S., 2004. Effects of sd1 and Ur1 (Undulate rachis -1) on lodging resistance  
615 and related traits in rice. *Breeding Science* 54, 333-340.

616 Niu, L., Feng, S., RU, Z., Li, G., Zhang, Z., Wang, Z., 2012. Rapid determination of single-stalk and  
617 population lodging resistance strengths and an assessment of the stem lodging wind speeds  
618 for winter wheat. *Field Crops Res.* 139, 1-8.

619 Niu L, Feng S, Ding W, Li G. 2016. Influence of Speed and Rainfall on Large-Scale Wheat Lodging from  
620 2007 to 2014 in China. [PLoS One](https://doi.org/10.1371/journal.pone.0157677) 11: e0157677.  
621 [www.ncbi.nlm.nih.gov/pmc/articles/PMC4930167](http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4930167)

622 Ogden, R.T., Miller, C.E., Takezawa, K., Ninomiya, S., 2002. Functional regression in crop lodging  
623 assessment with digital images. *J. Agric. Biol. Envir. Stat.* 7, 389-402.

624 Okuno, A., Hirano, K., Asano, K., Takase, W., Masuda, R., Morinaka, Y., Ueguchi-Tanaka, M., Kitano, H.,  
625 Matsuoka, M., 2014. New approach to increasing rice lodging resistance and biomass yield  
626 through the use of high gibberellin producing varieties. *PLoS ONE* 9, e86870.

627 Ookawa, T., Hobo, T., Yano, M., Murata, K., Ando, T., Miura, H., Asano, K., Ochiai, Y., Ikeda, M.,  
628 Nishitani, R., Ebitani, T., Ozaki, H., Angeles, E.R., Hirasawa, T., Matsuoka, M., 2010. New  
629 approach for rice improvement using a pleiotropic QTL gene for lodging resistance and yield.  
630 *Nat. Commun.* 1, 132.

631 Ookawa, T., Ishihara, K., 1992. Varietal difference of physical characteristics of the culm related to  
632 lodging resistance in paddy rice. *Jpn. J. Crop Sci.* 61, 419-425.

633 Ookawa, T., Ishihara, K., 1993. Varietal difference of the cell wall components affecting the bending  
634 stress of the culm in relation to the lodging resistance in paddy rice. *Jpn. J. Crop Sci.* 62, 378-  
635 384.

636 Peng, D., Chen, X., Yin, Y., Lu, K., Yang, W., Tang, Y., Wang, Z., 2014. Lodging resistance of winter wheat  
637 (*Triticum aestivum* L.) Lignin accumulation and its related enzymes activities due to the  
638 application of paclobutrazol or gibberellin acid. *Field Crops Res.* 157, 1-7.

639 Quang Duy, P., Abe, A., Hirano, M., Sagawa, S., Kuroda, E., 2004. Analysis of lodging-resistant  
640 characteristics of different rice genotypes grown under the standard and nitrogen-free basal  
641 dressing accompanied with sparse planting density practices. *Plant Prod. Sci.* 7, 243-251.

642 Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A., 2013. Yield trends are insufficient to double global  
643 crop production by 2050. *PLoS One.* 8:e66428. doi:10.1371/journal.pone.0066428

644 Setter, T. I., Laureles, E. V., Mazaredo, A. M., 1997. Lodging reduces yield of rice by self-shading and  
645 reduction of photosynthesis. *Field Crop Res.* 49, 95–106.

646 Shimono, H., Okada, M., Yamakawa, Y., Nakamura, H., Kobayashi, K., Hasegawa, T., 2007. Lodging in  
647 rice can be alleviated by atmospheric CO<sub>2</sub> enrichment. *Agriculture, Ecosystems & Environment*  
648 118, 223-230.

649 Sisler, W.W., Olson, P.J., 1951. A study of methods of influencing lodging in barley and the effect of  
650 lodging upon yield and certain quality characteristics. *Scientific Agriculture* 31, 177-186.

651 Sunohara, H., Miura, K., Wu, X., Saeda, T., Mizuno, S., Ashikari, M., Matsuoka, M., Kitano, H., 2006.  
652 Effects of Ssi1 gene controlling dm-type internode elongation pattern on lodging resistance  
653 and panicle characters in rice. *Breeding Science* 56, 261-268.

654 Wang, J., Zhu, J., Huang, R., Yang, Y., 2012. Investigation of cell wall composition related to stem lodging  
655 resistance in wheat (*Triticum aestivum* L.) by FTIR spectroscopy. *Plant Signaling & Behavior* 7,  
656 856-863.

657 Wu, W., Huang, J., Cui, K., Nie, L., Wang, Q., Yang, F., Shah, F., Yao, F., Peng, S., 2012. Sheath blight  
658 reduces stem breaking resistance and increases lodging susceptibility of rice plants. *Field Crops*  
659 *Res.* 128, 101-108.

660 Yanling, H., Yingyao, S., Guangle, S., Yangjuan, S., Weigang, W., Duopu, C., 2008. Study on the  
661 relationship between rice lodging resistance and culm traits & the yield factors. *Chin. Agric.*  
662 *Sci. Bull.* 24, 203-206.

663 Yano, K., Ookawa, T., Aya, K., Ochiai, Y., Hirasawa, T., Ebitani, T., Takarada, T., Yano, M., Yamamoto,  
664 T., Fukuoka, S., Wu, J., Ando, T., Ordonio, R.L., Hirano, K., Matsuoka, M., 2014. Isolation of a  
665 novel lodging resistance QTL gene involved in strigolactone signaling and its pyramiding with  
666 a QTL gene involved in another mechanism. *Molecular Plant* 8, 303–314.

- 667 Yoshida, S., 1981. Fundamental of Rice Crop Science. International Rice Research Institute, Los Baños,  
668 Laguna, Philippines, 269p.
- 669 Zhang, W.-j., Li, G.-h., Yang, Y.-m., Li, Q., Zhang, J., Liu, J.-y., Wang, S., Tang, S., Ding, Y.-f., 2014. Effects  
670 of nitrogen application rate and ratio on lodging resistance of super rice with different  
671 genotypes. *Journal of Integrative Agriculture* 13, 63-72.
- 672 Zhu, G., Li, G., Wang, D., Yuan, S., Wang, F., 2016. Changes in the lodging-related traits along with rice  
673 genetic improvement in China. PONE 0160104.  
674 <https://doi.org/10.1371/journal.pone.0160104>

675

676 **Tables**

677

678 **Table 1.**

679 **List of germplasm used in the study. Plant height, time from sowing to flowering and grain yield are**  
 680 **means from 2014 and 2015 dry seasons and serve as indicators of plant type. RYT, Breeders'**  
 681 **Replicated Yield Trials at IRRI; MET, Multi-Environment Trials of IRRI.**

Code	Accession name	Characteristics considered for selecting accessions (2013 pre-study, data not shown)	Origin	Plant height (cm)	Time to flowering (d)	Grain yield (t ha <sup>-1</sup> )
V1	NSIC Rc158	Local high-yielding check (IRRI New Plant Type)	Philippines	101	78,8	8,82
V2	NSIC Rc222	Local high-yielding check	Philippines	111	72,5	8,18
V3	CO 18	Yield, tall	India	174	79,5	3,80
V4	IR 77298-14-1-2	Yield in WS, short phyllochron	Philippines	112	69,5	7,00
V5	VELLAI SEENETTI	Yield in WS, medium tall, early	Sri Lanka	146	67,0	6,08
V6	UPL RI 5	Yield, medium tall	Philippines	159	81,5	6,34
V7	CT 6510-24-1-2	Yield in WS, medium tall, long phyllochron	Colombia	139	72,8	7,15
V8	WAS 33-B-B-15-1-4-5	Yield	Senegal	114	70,6	7,24
V9	HONDERAWALA	Tall, high pushing resistance	Sri Lanka	182	77,5	3,36
V10	CT 5805	Yield, thick stem	Colombia	117	80,8	7,76
V11	HABATAKI	Thick stem, low pushing resistance	Japan	101	69,2	7,01
V12	IR05N412	Yield, high pushing resistance, long internodes	Philippines	117	77,9	8,06
V13	IR07A179 (MET)	Yield, medium tall, high pushing resistance	Philippines	126	84,4	7,92
V14	IR07A253 (RYT)	High yield, thin stems	Philippines	97	70,3	8,01
V15	IR09N503 (RYT)	High yield	Philippines	106	74,1	8,44
V16	IR09N533 (RYT)	High yield, thin stems	Philippines	96	71,1	8,48
V17	IR10N225 (MET)	High pushing resistance, short internodes	Philippines	112	86,5	7,95
V18	PARAO	Thick stems	Uruguay	99	68,3	5,67
V19	PR37951-3B-37-1-2	High yield, low pushing resistance	Philippines	112	73,3	7,96
V20	ST12	Thick & long internodes, low pushing resistance	Japan	112	66,9	5,77

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683

684 **Table 2. Mean lodging (% canopy height reduction  $\pm$  SE) at 30, 45 and 60 km h<sup>-1</sup> wind speed by**  
 685 **Blaster for 20 genotypes and two years. S.L., spontaneous lodging. Box: Results of ANOVA (RCB)**  
 686 **with year and genotype as factors.**

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688

Code	Genotype	2014 dry season			2015 dry season			Mean
		30km/h	45km/h	60km/h	30km/h	45km/h	60km/h	
V01	NSIC Rc158	22.4 $\pm$ 6.7	55.3 $\pm$ 6.2	64.7 $\pm$ 5.2	33.2 $\pm$ 6.3	66.5 $\pm$ 2.4	75.5 $\pm$ 1.5	<b>52.9</b>
V02	NSIC Rc222	45.8 $\pm$ 5.3	66.1 $\pm$ 2.6	76.8 $\pm$ 1.1	53.6 $\pm$ 5.9	72.8 $\pm$ 2.9	79.4 $\pm$ 1.9	<b>65.7</b>
V03	ACCN 117691	S.L.	S.L.	S.L.	S.L.	S.L.	S.L.	
V04	ACCN 120987	50.8 $\pm$ 7.2	66.5 $\pm$ 4.0	72.2 $\pm$ 2.9	68.86.6	84.5 $\pm$ 2.4	87.8 $\pm$ 2.5	<b>71.8</b>
V05	ACCN 121152	57.1 $\pm$ 3.8	71.0 $\pm$ 3.8	75.6 $\pm$ 4.6	S.L.	S.L.	S.L.	<b>76.4</b>
V06	ACCN 121835	38.9 $\pm$ 4.1	66.8 $\pm$ 2.5	73.3 $\pm$ 5.1	59.3 $\pm$ 9.2	84.0 $\pm$ 2.8	88.8 $\pm$ 1.3	<b>68.5</b>
V07	ACCN 122025	37.3 $\pm$ 7.5	67.1 $\pm$ 1.6	70.5 $\pm$ 2.8	45.0 $\pm$ 5.2	74.9 $\pm$ 1.8	84.6 $\pm$ 1.7	<b>63.2</b>
V08	ACCN 122292	46.6 $\pm$ 7.6	66.7 $\pm$ 5.9	74.6 $\pm$ 4.3	67.5 $\pm$ 11.2	82.2 $\pm$ 3.0	87.6 $\pm$ 2.3	<b>70.9</b>
V09	ACCN 47372	S.L.	S.L.	S.L.	S.L.	S.L.	S.L.	
V10	CT 5805	10.4 $\pm$ 3.1	36.5 $\pm$ 6.9	44.7 $\pm$ 6.7	19.2 $\pm$ 5.7	43.4 $\pm$ 3.7	57.4 $\pm$ 1.0	<b>35.3</b>
V11	Habataki	25.7 $\pm$ 5.1	50.3 $\pm$ 4.5	59.4 $\pm$ 5.7	17.0 $\pm$ 4.0	62.2 $\pm$ 1.3	74.0 $\pm$ 2.4	<b>48.1</b>
V12	IR05N412	22.3 $\pm$ 5.3	52.8 $\pm$ 10.7	66.2 $\pm$ 6.9	41.7 $\pm$ 6.5	71.5 $\pm$ 5.9	81.9 $\pm$ 4.1	<b>56.1</b>
V13	IR07A179	49.2 $\pm$ 5.8	74.8 $\pm$ 3.8	81.4 $\pm$ 3.9	61.3 $\pm$ 6.1	83.7 $\pm$ 2.4	86.9 $\pm$ 2.0	<b>72.9</b>
V14	IR07A253	35.3 $\pm$ 9.0	57.8 $\pm$ 6.9	66.0 $\pm$ 7.1	47.0 $\pm$ 9.9	69.2 $\pm$ 4.8	75.7 $\pm$ 2.7	<b>58.5</b>
V15	IR09N503	19.4 $\pm$ 2.5	50.7 $\pm$ 2.1	61.6 $\pm$ 1.1	37.3 $\pm$ 11.3	71.7 $\pm$ 2.9	76.6 $\pm$ 2.0	<b>52.9</b>
V16	IR09N533	12.7 $\pm$ 2.8	35.0 $\pm$ 10.7	48.4 $\pm$ 9.4	55.4 $\pm$ 4.5	74.1 $\pm$ 3.0	80.8 $\pm$ 1.3	<b>51.1</b>
V17	IR10N225	11.4 $\pm$ 2.2	31.8 $\pm$ 7.0	39.9 $\pm$ 4.7	25.7 $\pm$ 0.9	61.0 $\pm$ 5.8	79.1 $\pm$ 2.9	<b>41.5</b>
V18	PARAO	15.2 $\pm$ 11.6	41.4 $\pm$ 10.1	47.9 $\pm$ 8.2	6.74 $\pm$ 2.1	30.9 $\pm$ 8.1	42.2 $\pm$ 8.3	<b>30.7</b>
V19	PR37951-3B-37-1-2	27.9 $\pm$ 0.8	57.5 $\pm$ 3.4	68.6 $\pm$ 2.6	36.9 $\pm$ 3.5	69.6 $\pm$ 4.3	78.3 $\pm$ 2.4	<b>56.5</b>
V20	ST12	22.0 $\pm$ 5.7	46.1 $\pm$ 3.5	58.4 $\pm$ 3.7	42.6 $\pm$ 4.0	70.0 $\pm$ 3.2	77.7 $\pm$ 3.8	<b>52.8</b>
Mean		<b>30.6<math>\pm</math>5.3</b>	<b>55.2<math>\pm</math>5.3</b>	<b>63.9<math>\pm</math>4.8</b>	<b>42.2<math>\pm</math>5.7</b>	<b>68.9<math>\pm</math>3.4</b>	<b>77.3<math>\pm</math>2.5</b>	

ANOVA table	30km/h		45km/h		60km/h	
Factor (DF)	F-value	P	F-value	P	F-value	P
Replication (3)	0.13	0.937	2.74	0.215	6.77	0.0753
Year (1)	3.38	0.163	48.31	0.0061	139.0	0.0013
Genotype (17)	12.46	0.0000	14.34	0.0000	18.1	0.0000
Y x G (17)	5.87	0.0000	10.09	0.0000	14.7	0.0000
CV%	33.0		16.7		12.5	

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694 **Table 3.**

695 **Broad sense heritability ( $H^2$ ) of lodging response to Blaster within years and across two years (2014**  
696 **and 2015). Values are presented with or without inclusion of genotypes that lodged spontaneously**  
697 **before blasting. Where included, their reduction in canopy height due to lodging was calculated**  
698 **from canopy height observed at flowering (non-lodged) and canopy height observed at the time of**  
699 **blasting, two weeks later.**

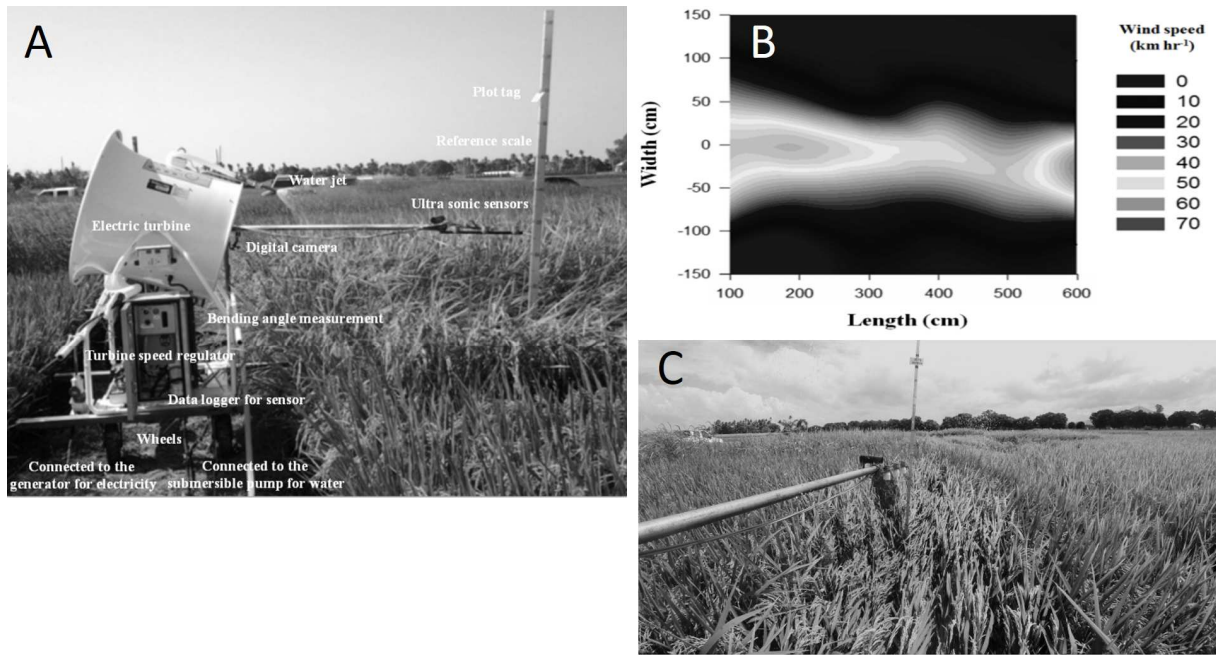
Wind speed	All genotypes incl. spontaneous lodging			Cases of spontaneous lodging excluded		
	30 km h <sup>-1</sup>	45 km h <sup>-1</sup>	60 km h <sup>-1</sup>	30 km h <sup>-1</sup>	45 km h <sup>-1</sup>	60 km h <sup>-1</sup>
2014	0.69	0.83	0.86	0.69	0.74	0.81
2015	0.86	0.94	0.99	0.77	0.93	0.92
Both years	0.29	0.18	0.13	0.35	0.28	0.29

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702 **Figures**

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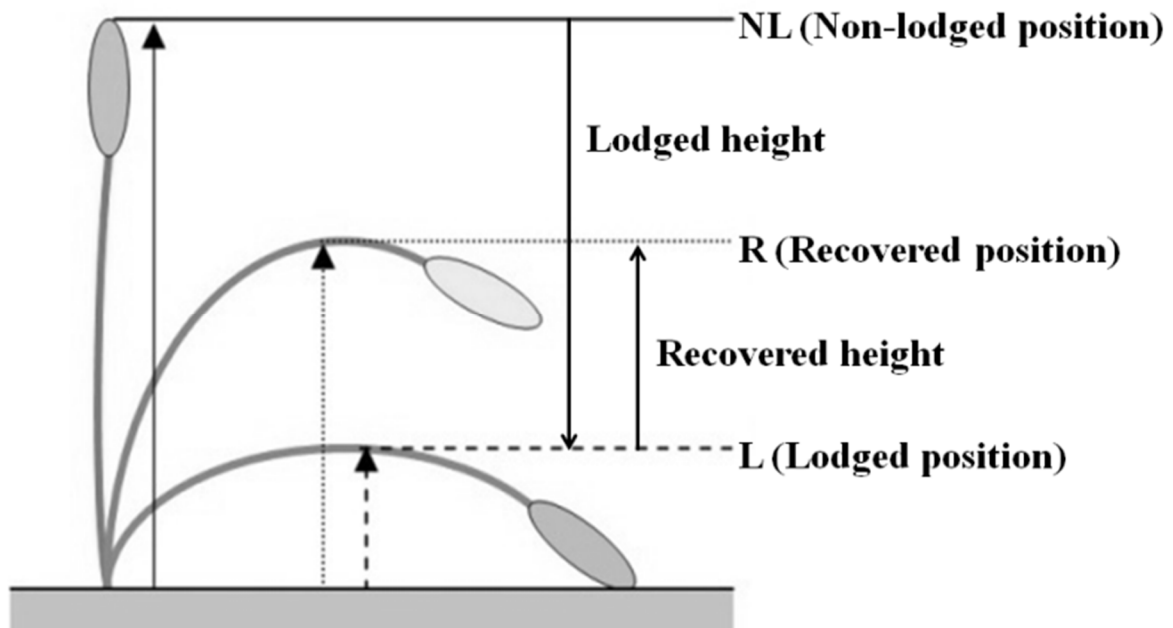
704

705 **Fig. 1. Field setup and components of the Blaster (A), wind channel of the Blaster as mapped by**  
706 **portable anemometer (B), and the Blaster-induced lodging in the field as seen from Blaster (C) .**

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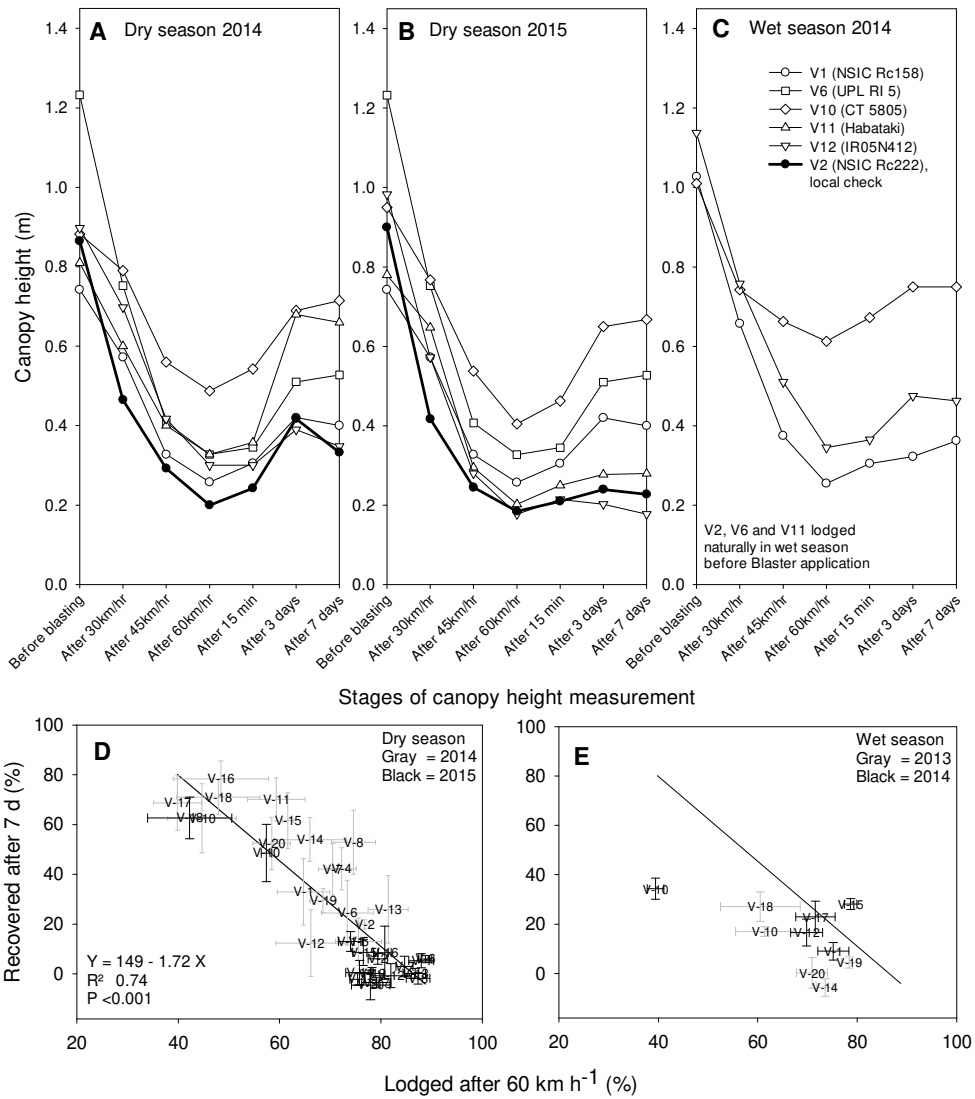
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711 **Fig. 2. Schematic diagram of lodging and recovery from lodging. “NL” is the canopy height of non-**  
712 **lodged before blasting, “L” is the canopy height at lodged position soon after blasting, and “R” is the**  
713 **canopy height at recovered position.**

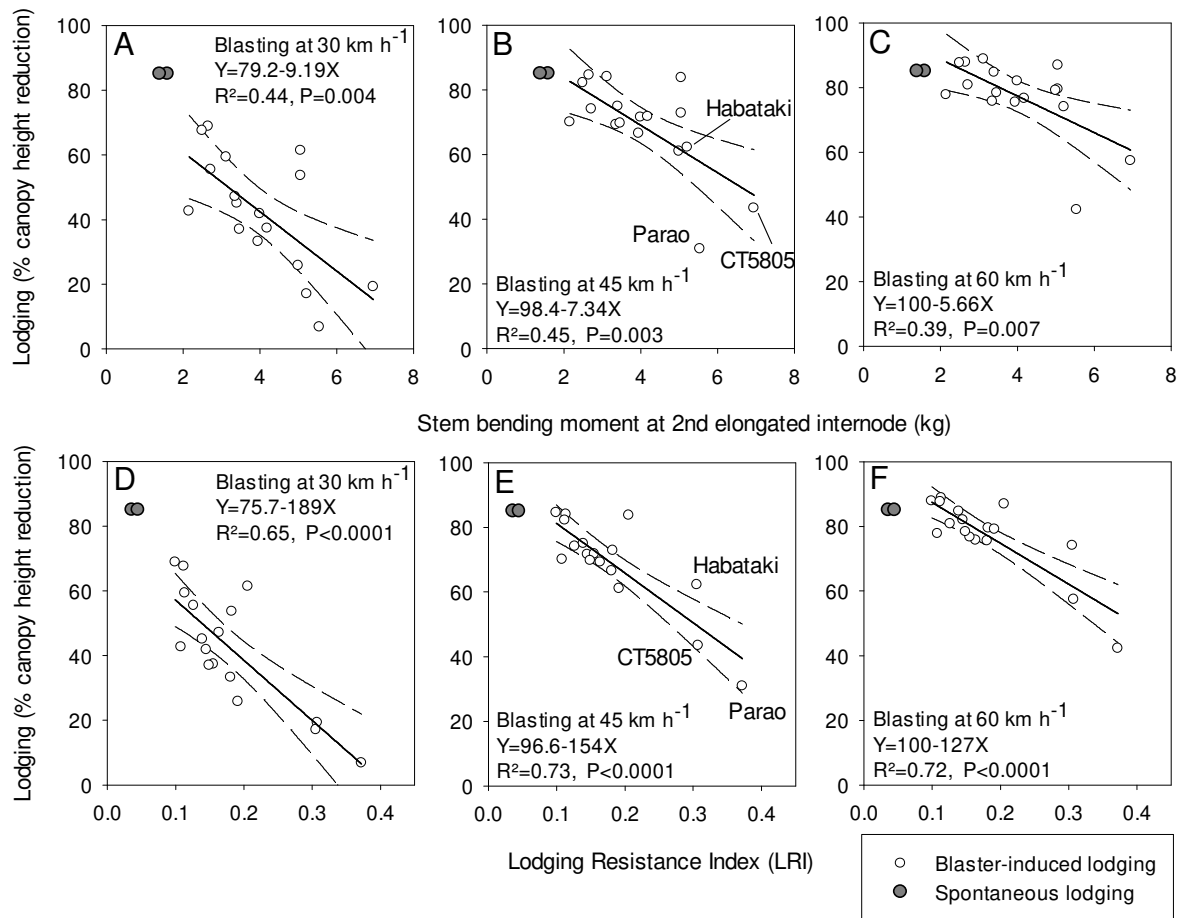
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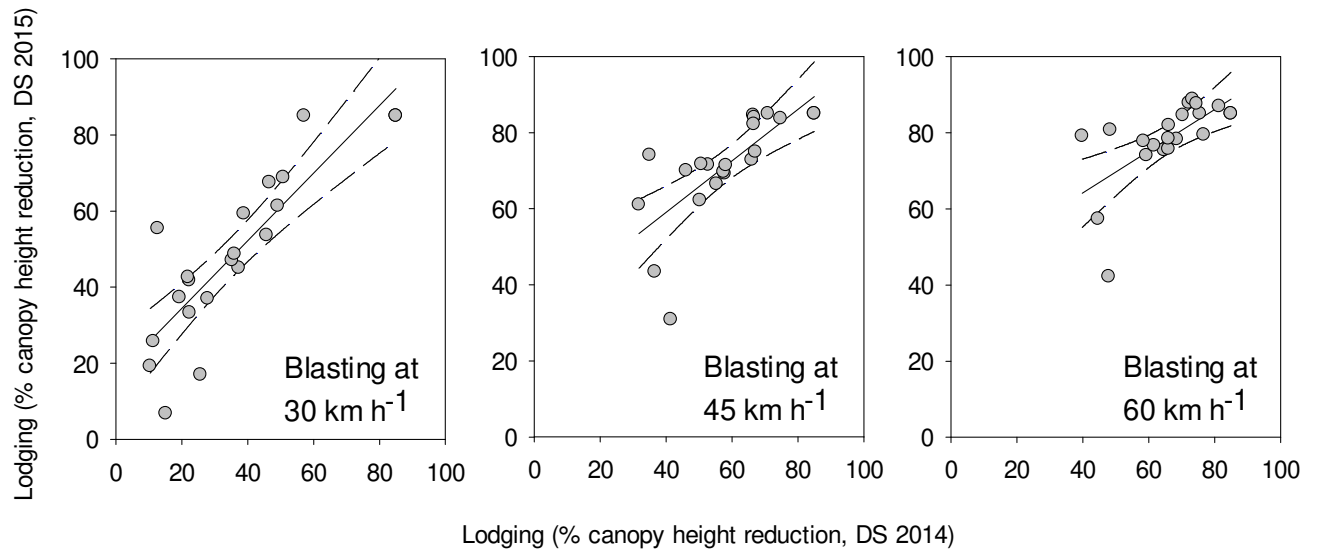
717 **Fig. 3. Figures A, B, C: Variation in canopy height before and after blasting for a subset of 6**  
 718 **contrasting genotypes (A, dry season 2014; B, dry season 2015; C, wet season 2014). The local check**  
 719 **V2 is highlighted with bold lines. In wet season, only genotypes are shown that did not lodge**  
 720 **spontaneously. Figures C, E: Relationship between extent of lodging and subsequent recovery (%**  
 721 **canopy height). Vertical and horizontal error bars are SEM (n=4). In Fig. D, gray represents DS 2014**  
 722 **and black represent DS 2015. In Fig. E, gray represent WS 2013 and black represents WS 2014. The**  
 723 **linear regression line in the Fig. E is replicated from Fig. D as reference. For genotype code and names**  
 724 **refer to Table 1. Lodging and recovery percentage were calculated using equations 1 and 2.**

725



726

727 **Fig. 4. Relationship between lodging induced by Blaster and stem bending moment (A, B, C) and**  
728 **Lodging Resistance Index (LRI) (D, E, F), based on 3 wind speeds for 20 genotypes. Cases of**  
729 **spontaneous lodging before Blaster treatment (filled symbols) were not included in correlations**  
730 **(regression line and confidence interval at P=0.05). All data for dry season 2015.**



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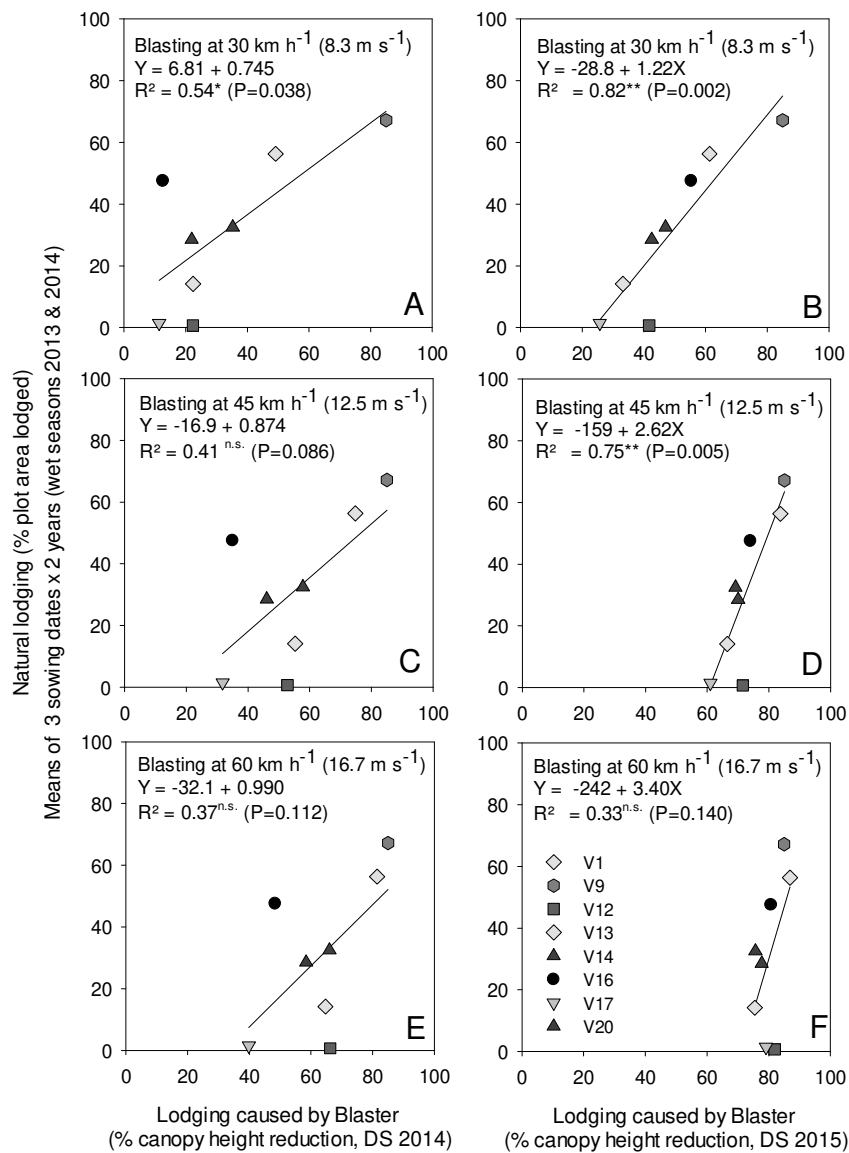
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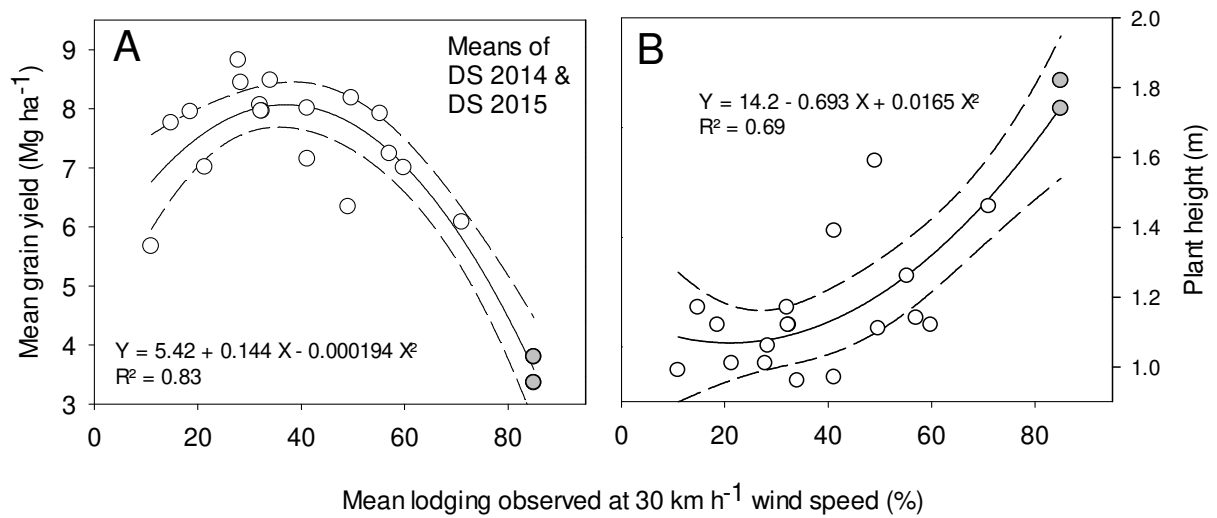
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**Fig. 5. Comparison of induced lodging results between DS 2014 and DS 2015 for the same genotypes and identical setup. Linear regression analyses: 30km/h :  $Y=0.889X+16.6$ ,  $R^2=0.733$ ,  $P<0.0001$ ; 45km/h :  $Y=0.677+31.94$ ,  $R^2=0.541$ ,  $P<0.001$ ; 60km/h :  $Y=0.549X+42.25$ ,  $R^2=0.420$ ,  $P<0.01$ .**



738

739 **Fig. 6. Validation of induced lodging by Blaster (ACE: 2014, BDF: 2015 dry seasons) with mean**  
 740 **natural lodging observed in 6 wet season environments (3 sowing dates each in 2013 and 2014);**  
 741 **for a subset of 8 genotypes.**



742

743 **Fig. 7. Relationship between grain yield (A) and plant height (B) vs. lodging response at  $30 \text{ km h}^{-1}$**   
 744 **wind speed across 20 genotypes. All data are means for DS 2014 and DS 2015 experiments. Filled**  
 745 **symbols indicate cases of spontaneous lodging occurring before Blaster treatment. Grain yields were**  
 746 **measured on plot sectors where lodging was not induced by Blaster. Dashed lines indicate 95%**  
 747 **confidence interval.**

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749 **Supplemental materials**

750

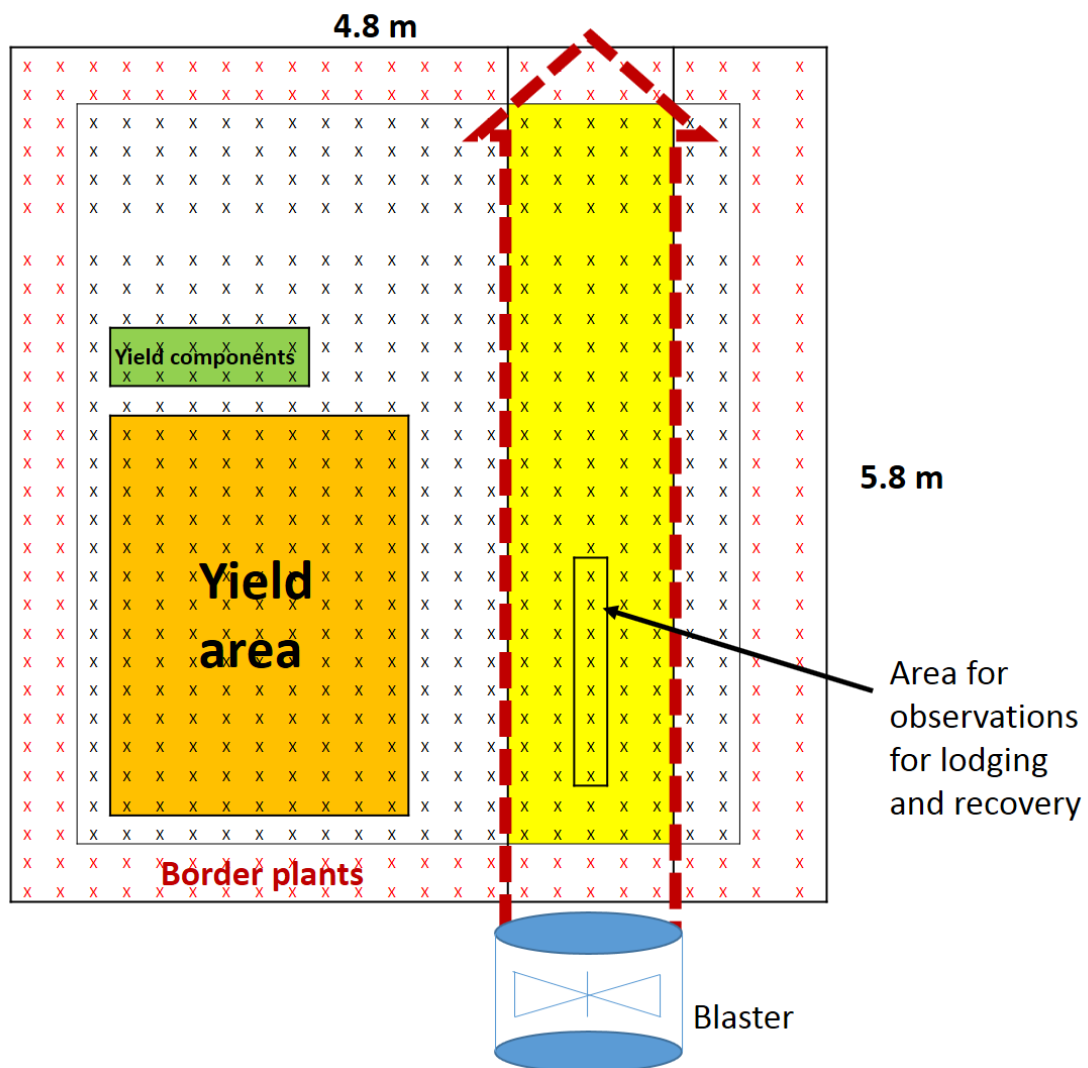
751 **Table S1**

752 **Pearson correlations (R) of lodging induced by Blaster at three wind speeds vs. various**  
 753 **morphological traits at maturity, observed on plot sectors not affected by Blaster. Cases of**  
 754 **spontaneous lodging were not included. IN, internode; DW, dry weight. Significant correlations**  
 755 **(P<0.05) are printed bold.**

	Means 2 years			2014			2015		
	30	45	60	30	45	60	30	45	60
Blaster wind speed (km h <sup>-1</sup> )									
Culm length	<b>0.54</b>	<b>0.54</b>	<b>0.49</b>	<b>0.49</b>	<b>0.54</b>	<b>0.45</b>	0.40	0.42	0.41
Plant height	<b>0.53</b>	<b>0.55</b>	<b>0.51</b>	<b>0.48</b>	<b>0.53</b>	<b>0.45</b>	0.45	<b>0.47</b>	<b>0.48</b>
Stem diameter (2 <sup>nd</sup> IN)	<b>-0.50</b>	<b>-0.48</b>	<b>-0.48</b>	-0.35	-0.37	-0.39	<b>-0.47</b>	-0.43	-0.41
Culm diameter (2 <sup>nd</sup> IN)	-0.15	-0.14	-0.16	-0.04	-0.03	-0.05	-0.18	-0.23	-0.29
Sheath thickness (2 <sup>nd</sup> IN)	<b>-0.50</b>	<b>-0.48</b>	-0.45	<b>-0.50</b>	<b>-0.56</b>	<b>-0.55</b>	-0.36	-0.27	-0.20
Panicles per hill	0.11	0.05	0.10	0.09	-0.01	0.09	0.22	0.21	0.22
Aboveground DW (mat.)	<b>0.49</b>	0.37	0.32	0.05	0.17	0.16	0.02	0.12	0.20
Grain yield (maturity)	-0.15	-0.01	0.08	-0.20	-0.09	-0.02	0.20	0.29	0.34
Pearson critical R (P=0.05) = 0.47									

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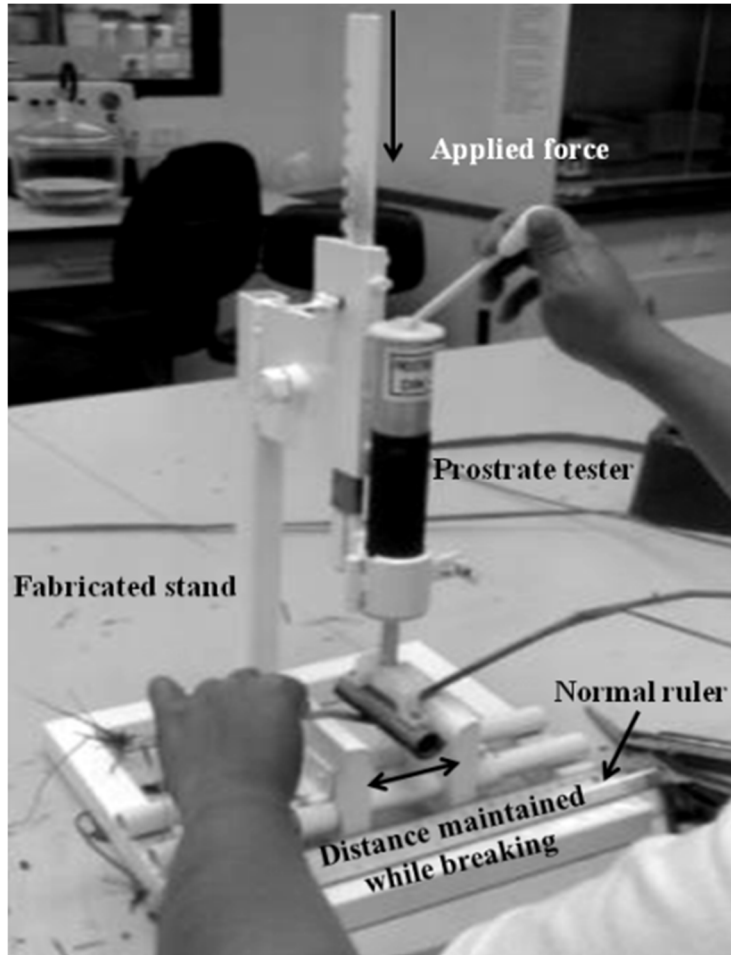
759 **Supplemental Fig. S1. Experimental plot layout and locations of sampling.**

760

761

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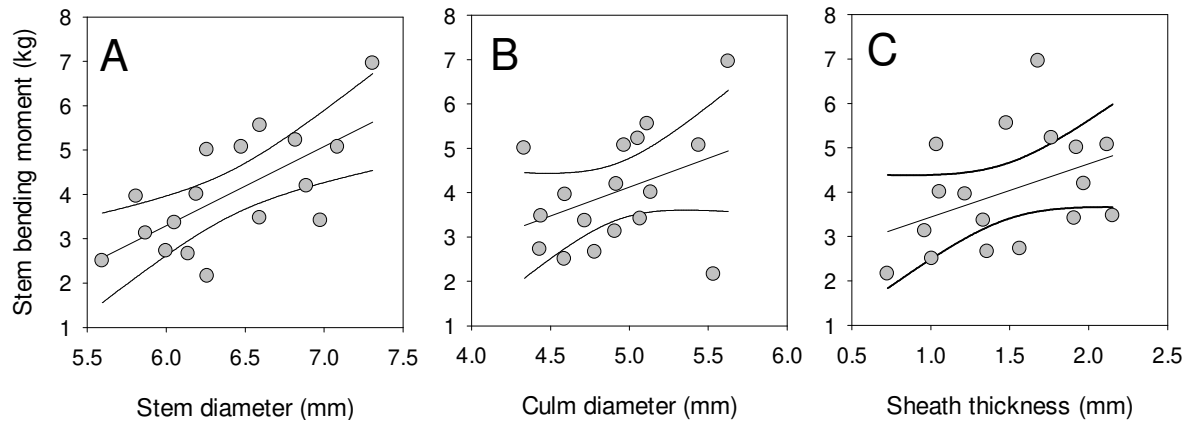
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765 **Supplemental Fig. S2. The load-testing device developed to measure stem bending moment at**  
766 **breakage.**

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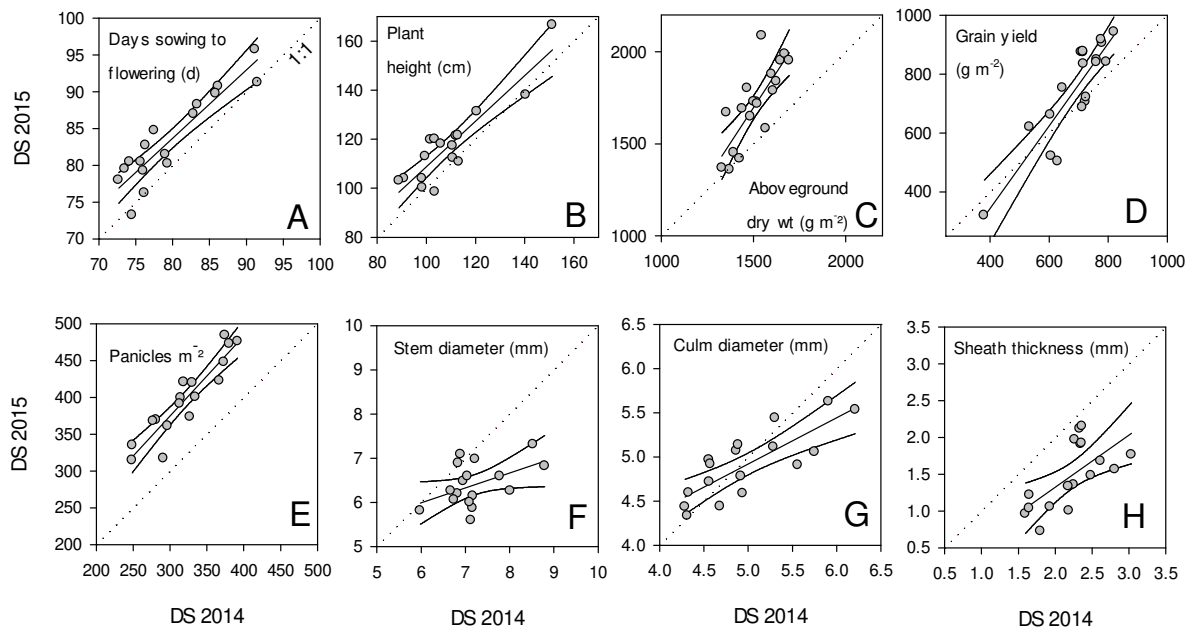


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769 **Supplemental Fig. S3. Relationship between stem bending moment for breakage at the 2<sup>nd</sup>**  
 770 **elongated internode (counting from bottom) and stem diameter (A), culm diameter (B) and the**  
 771 **thickness of the layer of leaf sheaths surrounding the culm (C) in the DS 2015. Lines indicate**  
 772 **regression line and 5% confidence interval.**

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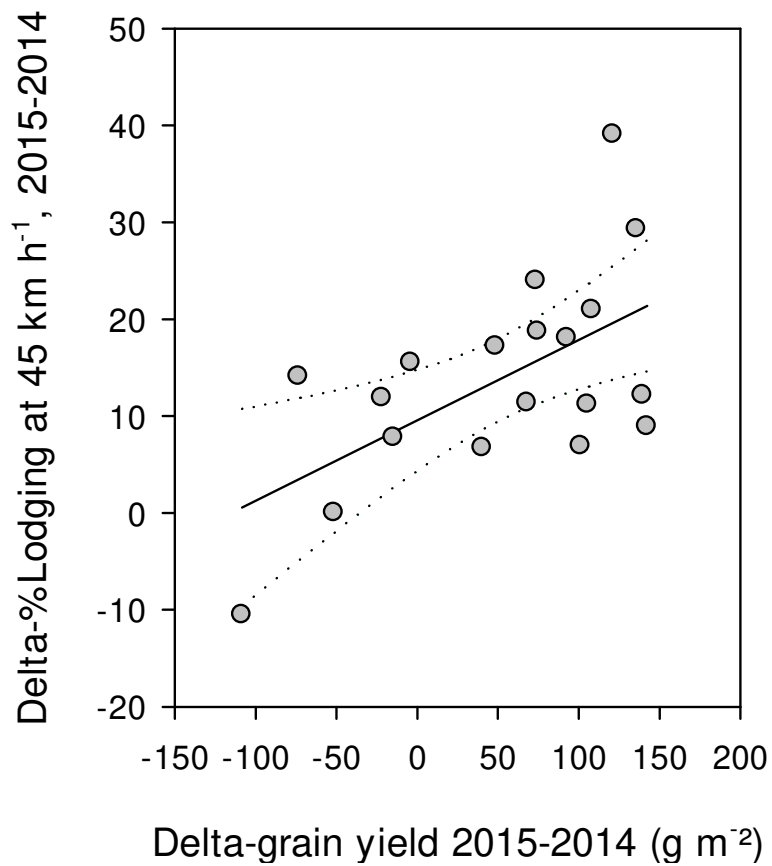


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776 **Fig. S4. Linear correlations for phenological and morphological crop traits between DS 2015 and DS**  
777 **2014.**

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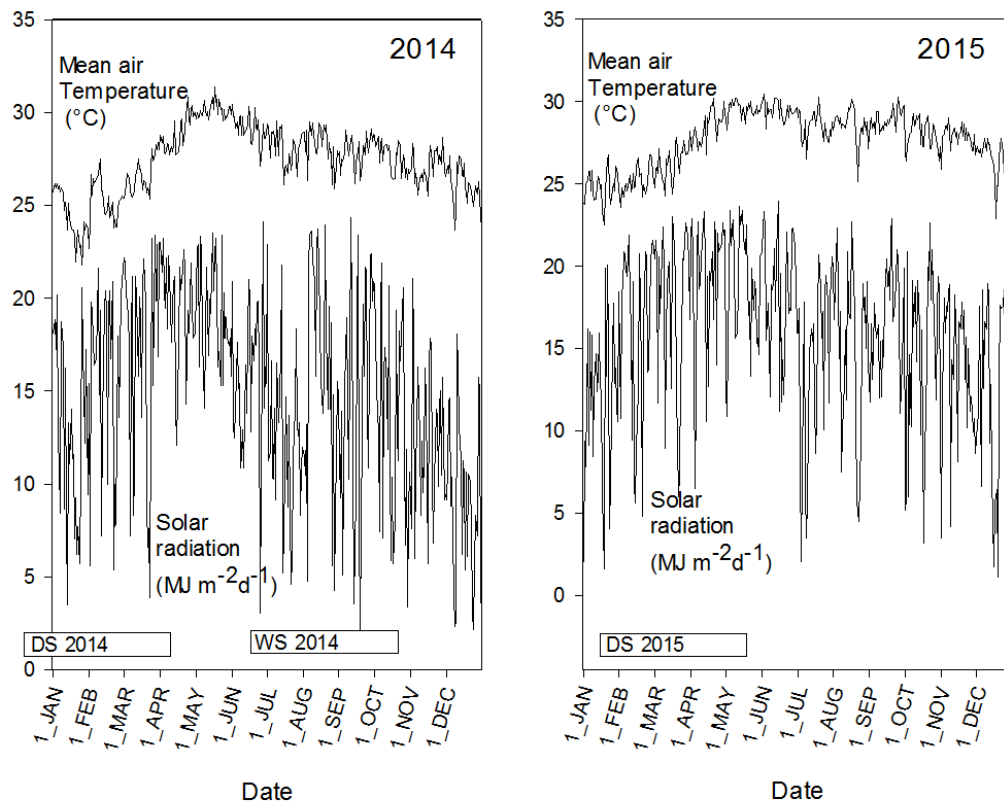


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782 **Supplemental Fig. S5. Relationship between the DS 2015-2014 annual difference in grain yield and**  
783 **the annual difference in induced lodging at 45 km h<sup>-1</sup> in the dry season. Correlation:**

784 **Y=9.55+0.083X, R<sup>2</sup>=0.35, P<0.01**

785



787

788 **Supplemental Fig. S6. Mean daily air temperature and solar radiation at the experimental site in**  
789 **2014 and 2015. The cropping periods are indicated.**

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**Lodging  
generated  
by Blaster**



794

795 **Supplemental Pic. S1. Lodging generated by Blaster.**