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

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Abstract

Lodging is a major yield-reducing factor in rice systems, particularly under intensified cultivation using high-yielding cultivars. It is usually triggered by rainstorms during grain filling. The study of natural lodging is difficult due to unpredictable weather. Proxy traits for lodging resistance such as stem morphology and breaking moment have limited validity because lodging is complex. We present a new mobile, low-cost field methodology called Blaster. It uses a wind turbine creating a 1m wide and 6m deep wind path in the field with wind speed adjustable to 30, 45 and 60 km h⁻¹. Water injected into the air stream provides for wetting of the crop. A measurement cycle takes ca. 10 min per plot. The lodging response of 20, mostly high-yielding but diverse rice genotypes was studied in 2013, 2014 and 2015 under irrigated transplanted conditions in the Philippines. Genotypic responses were reproducible between seasons and were predictive of natural lodging observed in the wet season for a subset of 8 genotypes. Cultivars PARA0 and CT 5805 from Latin America consistently stood out for superior lodging resistance. Across genotypes, morphological traits such as plant height, biomass or stem diameter were not or poorly predictive of lodging induced by Blaster. The best single proxy trait, stem-base bending moment at breakage (BM), explained about 40% of Blaster-induced lodging, and the Lodging Resistance Index composed of plant height, wet biomass and BM explained about 70%. We propose that Blaster is a reliable tool to evaluate crop lodging resistance as affected by genotype, cultural practices or season.

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

1. Introduction

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

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

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

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

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

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

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

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

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

2. Materials and Methods

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

2.1 Rice-blaster

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

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

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

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

(Fig. 1 about here)

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

Equation 1

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

Whereby:

NL, canopy height Non-Lodged [m]

L, canopy height Lodged [m]

Equation 2

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

Whereby:

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

NL, canopy height Non-Lodged [m]

L, canopy height Lodged after blasting [m] (where not stated otherwise, blasting at 60 km h⁻¹)

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

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

(Fig. 2 about here)

2.2 Load-testing device

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

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

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

2.3 Proxy traits and index calculations to evaluate lodging resistance

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

Stem morphology:

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

Stem bending moment:

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

Lodging resistance index:

Lodging resistance index (LRI) was calculated for the crop around the time of blasting according to (Ookawa and Ishihara, 1992) using Equation 3. It expresses the ratio of BM_i (expressing the force needed to break the stem) over the whole-plant bending moment, or fresh-weight based lever, which in turn is equal to the product of the mean culm length and the fresh weight of the crop above the internode(i). BM_i was measured for the 2nd and 3rd elongated internode (counting from bottom). We used the BM₂ in our calculations, which gave very similar results as for BM₃ (data not shown).

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

Equation 3

$$LRI = \frac{BM_i}{FW * CL}$$

Whereby:

LRI, Lodging Resistance Index

BM_i, Bending Moment at internode(i) [kg cm]

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

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

Crop yield at maturity:

Grain yield was determined from a 5 m² on each plot in areas unaffected by the wind channel of the Blaster (Fig. S1). Aboveground dry weight and harvest index at maturity were determined for 12 hills adjacent to the grain yield area after drying of samples in ovens (60 °C until constant weight).

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

Experiments were conducted on K4 block of IRRI experiment station, Los Baños, Philippines (14°11' N, 121°15' E, 21m asl). Genotypes were arranged in a randomized complete block design (RCBD) with 4 replications. Individual plot size was 4.8 m x 5.8 m (27.84 m²). The plots had a long-term history of rice monoculture (2 crops/year) with complete irrigation (flooding) and the soil was reasonably deep for irrigated rice (plow pan at ca. 30-40 cm). Fourteen-day old seedlings were transplanted from a seedbed 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 m⁻²).

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

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

2.5 Validation experiment in wet season

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

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

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

2.6 Genetic materials

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

(Table 1 about here)

2.7 Data analysis and graphical presentation

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

3. Results

3.1 Dynamics of crop lodging upon Blaster application

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

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

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

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

(Fig. 3 about here)

3.2 Relationship between Blaster response and lodging-related crop traits

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

(Fig. 4 about here)

Compared to BM₂, morphological traits such as stem diameter were less predictive of induced lodging with genotypes excluded that lodged spontaneously (Table S1). Plant height and culm length (from base to neck node) had R values around +0.5 (R^2 of 0.25) and were mostly significant ($P < 0.05$). Stem mean diameter at the 2nd internode had similar R values but they were negative, whereby the minor and major diameter had similar effects (only mean diameter presented in Table S2). Of the two component traits of stem diameter, the thickness of the sheath layer around the culm accounted for the correlation whereas culm diameter had no effect. Panicle number per hill, aboveground dry weight and grain yield had much lower correlations than plant height and stem thickness related traits.

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

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

3.3 Repeatability of genotypic responses to Blaster

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

(Fig. 5 about here)

According to ANOVA (box in Table 2), block effects were not significant. Year effects were not significant at 30 km h⁻¹ blasting but highly significant ($P<0.01$) at higher wind speeds. Genotype effects and genotype x year interactions were highly significant ($P<0.0001$) for all wind speeds. The factor interaction was in large part due to V17 which lodged little in 2014 and much in 2015 (Table 2).

The mean coefficient of variance was highest at 30 km h⁻¹ and decrease at higher wind speeds. Genotypic seasonal means (\pm SE) are presented in Table 2 and show that V10 and V18 stood out consistently in terms of lower lodging.

(Table 2 about here)

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

(Table 3 about here)

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

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

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

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

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

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

3.5 Validation of Blaster with natural lodging

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

(Fig. 6 about here)

The strongest correlations were observed for blasting at 30 km h⁻¹, whereby correlations were better 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 45 km h⁻¹ was also highly significantly correlated with natural lodging ($P=0.005$). However, correlations declined at higher Blaster wind speeds. For both years and all for Blaster wind speeds, the least lodging genotype after blasting (V17) also showed the least natural lodging, and the most lodging genotype after blasting showed the most natural lodging in the wet season. When two-year means of blasting results were compared with two-year means of natural lodging (data not 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 blasting at 30, 45 and 60 km h⁻¹, respectively. Overall, induced lodging by Blaster in 2015 dry season was highly predictive of natural lodging in wet season, but induced lodging in 2014 was less predictive for unknown reasons.

3.7 Lodging resistance vs. grain yield

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

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

(Fig. 7 about here)

4. Discussion

4.1 Advantages and limitations of Blaster methodology

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

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

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

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

From a practical point of view, the Blaster method is rapid enough (5-10 min per measurement, plus the time to move to the next plot) to measure lodging resistance on large agronomic experiments, but too time consuming to be applied to genetic phenotyping trials which have 100s to 1000s of plots. The method also has substantial space requirements, as the 1-m wide wind channel calls for a plot width 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 equipment. These requirements can be easily met for agronomic experiments and the evaluation of advanced breeding materials, but may be prohibitive for phenotyping or varietal screening objectives. Likewise, the destructive nature of the measurement may not be compatible with all experimental designs.

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

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

4.2 Repeatability

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

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

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

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

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

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

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

4.4 Genotypic differences in lodging resistance

To our knowledge, to standard lodging resistance check cultivars are available for tropical rice (generally indica types), contrary to temperate, japonica-type rices that are well studied in Japan. We thus relied on breeders' experience (notably from multi-environment trials) and morphological criteria such as stem thickness to compose the diverse panel of 20 cultivars.

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

4.5 Potential applications of Blaster in crop improvement

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

4.6 Potential applications of Blaster in agronomy

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

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

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

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	52.9
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	65.7
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	68.8 \pm 6.6	84.5 \pm 2.4	87.8 \pm 2.5	71.8
V05	ACCN 121152	57.1 \pm 3.8	71.0 \pm 3.8	75.6 \pm 4.6	S.L.	S.L.	S.L.	76.4
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	68.5
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	63.2
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	70.9
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	35.3
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	48.1
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	56.1
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	72.9
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	58.5
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	52.9
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	51.1
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	41.5
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	30.7
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	56.5
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	52.8
Mean		30.6\pm5.3	55.2\pm5.3	63.9\pm4.8	42.2\pm5.7	68.9\pm3.4	77.3\pm2.5	

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	

Table 3.

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

Wind speed	All genotypes incl. spontaneous lodging			Cases of spontaneous lodging excluded		
	30 km h ⁻¹	45 km h ⁻¹	60 km h ⁻¹	30 km h ⁻¹	45 km h ⁻¹	60 km h ⁻¹
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

Figures

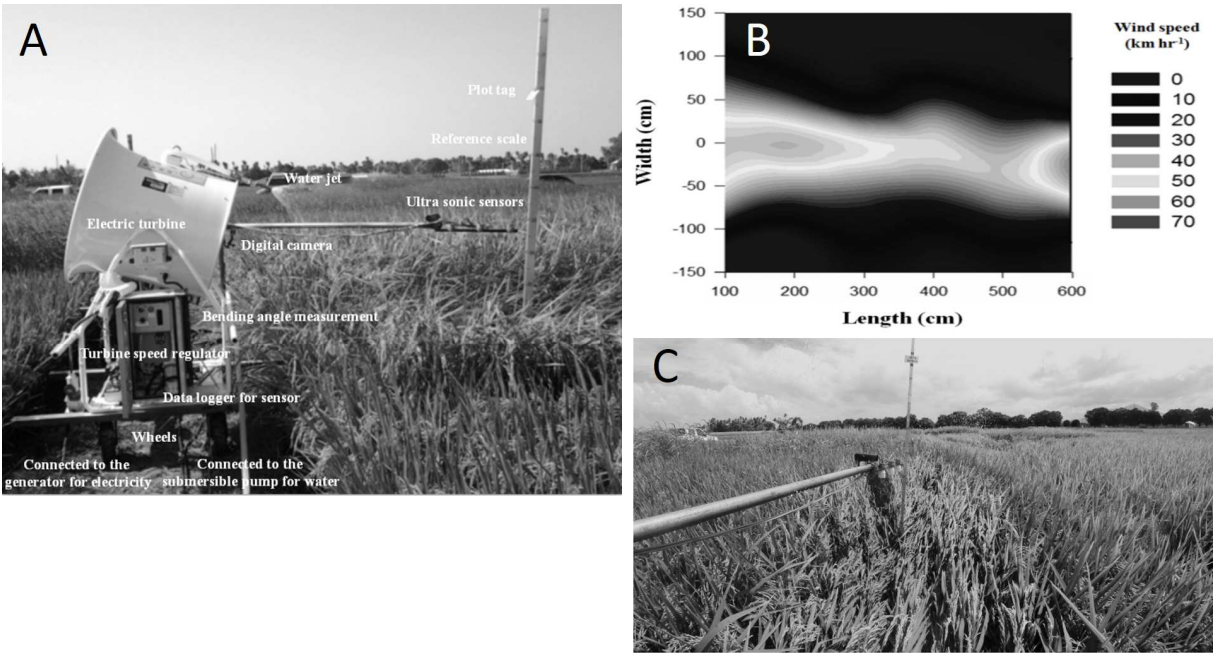
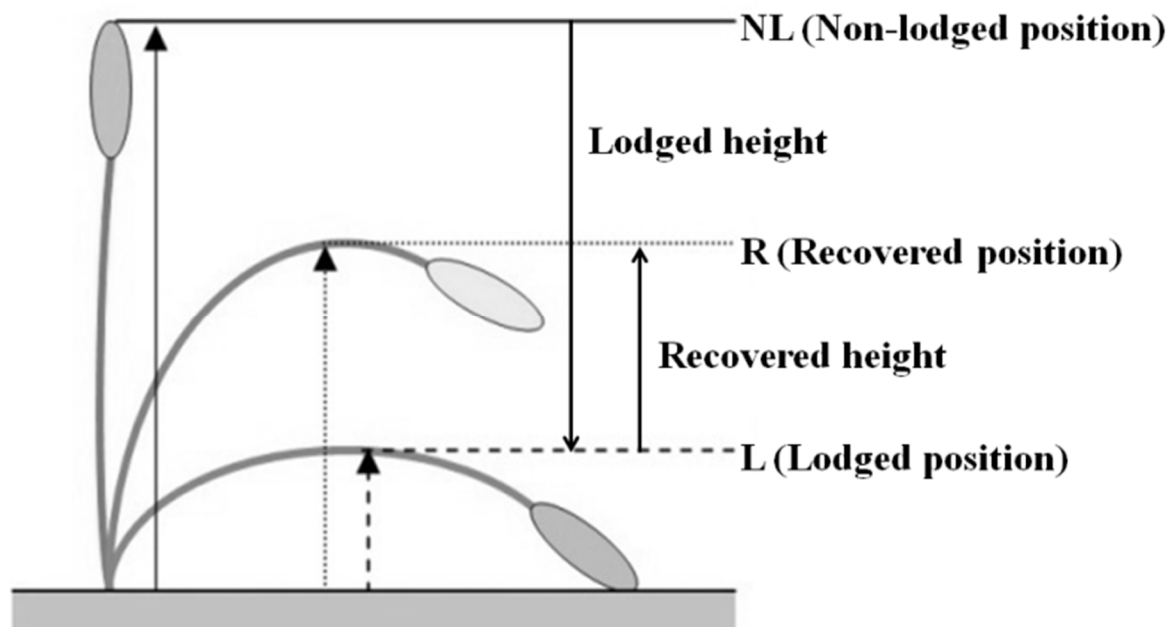


Fig. 1. Field setup and components of the Blaster (A), wind channel of the Blaster as mapped by portable anemometer (B), and the Blaster-induced lodging in the field as seen from Blaster (C) .

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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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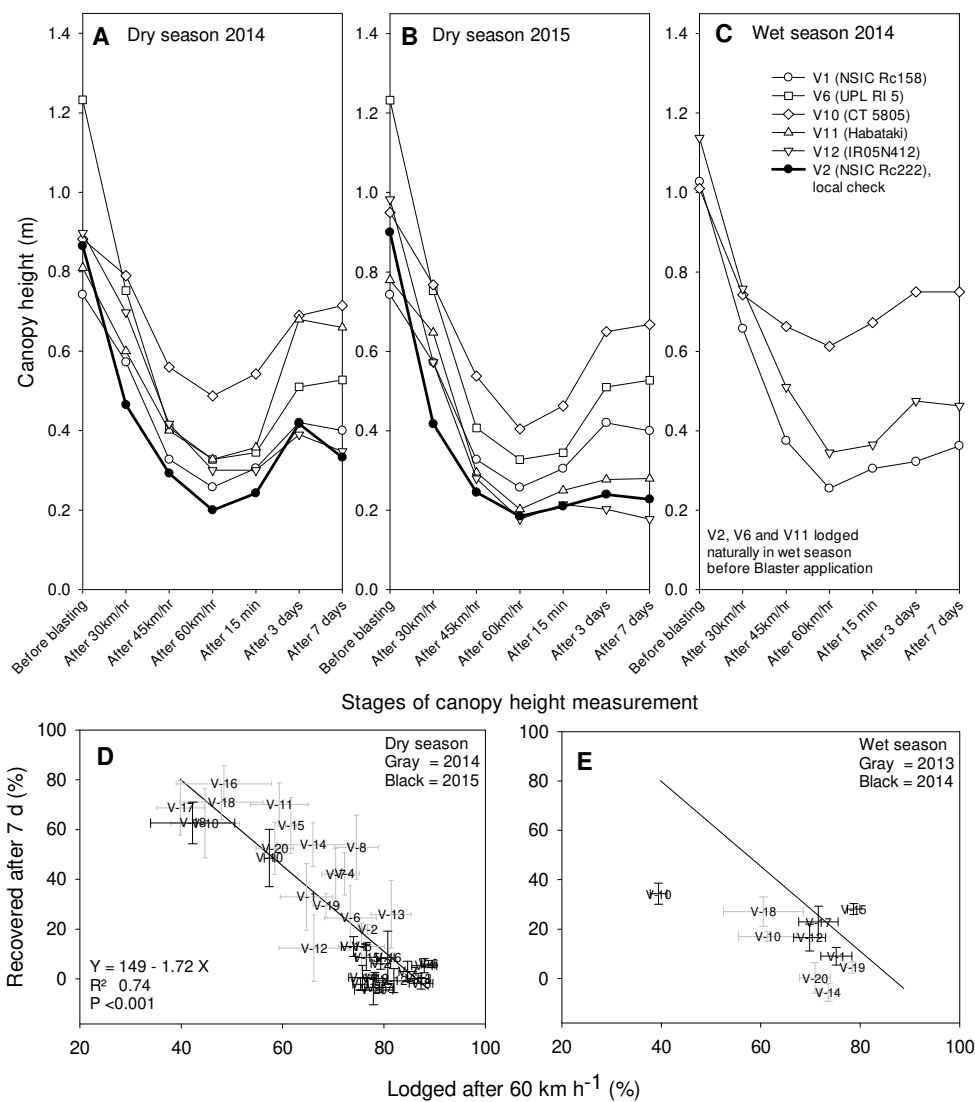


Fig. 3. Figures A, B, C: Variation in canopy height before and after blasting for a subset of 6 contrasting genotypes (A, dry season 2014; B, dry season 2015; C, wet season 2014). The local check V2 is highlighted with bold lines. In wet season, only genotypes are shown that did not lodge spontaneously.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

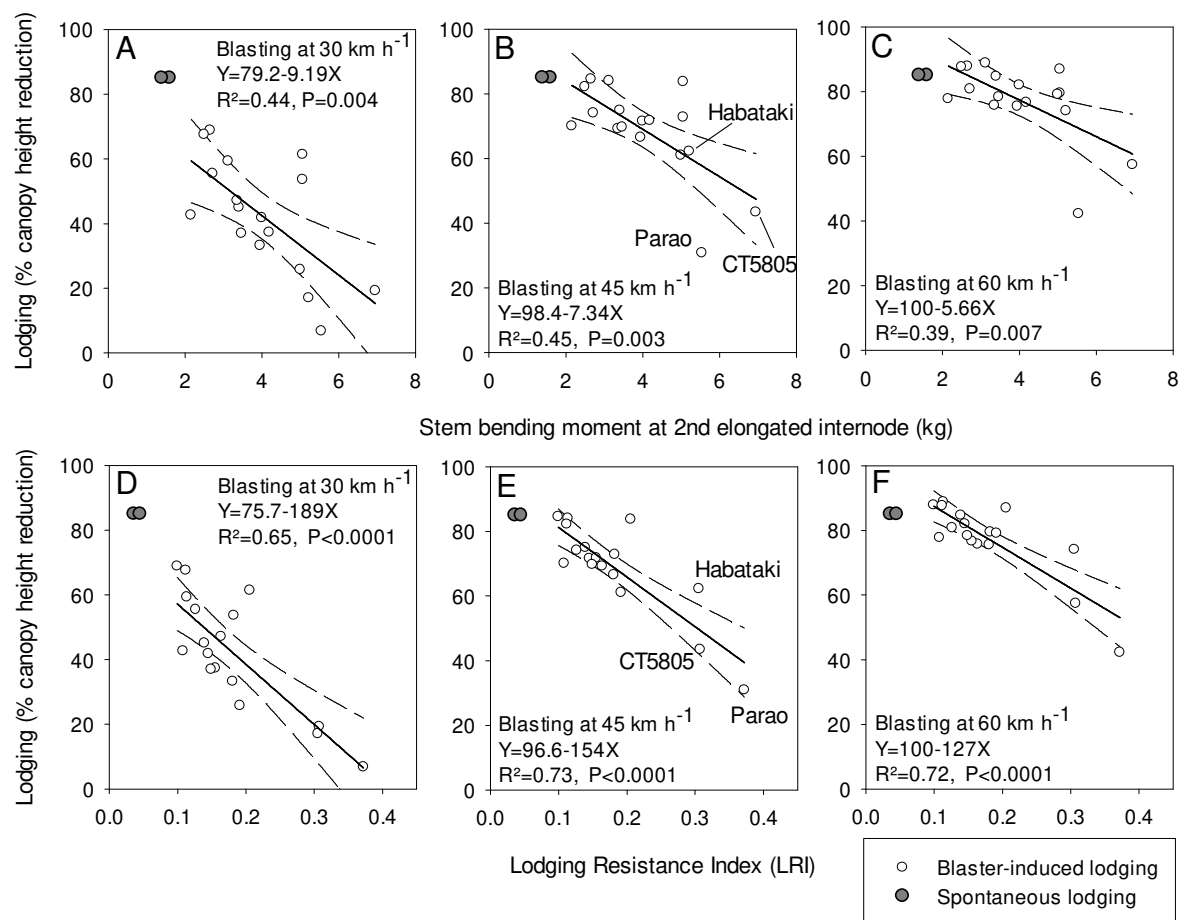


Fig. 4. Relationship between lodging induced by Blaster and stem bending moment (A, B, C) and Lodging Resistance Index (LRI) (D, E, F), based on 3 wind speeds for 20 genotypes. Cases of spontaneous lodging before Blaster treatment (filled symbols) were not included in correlations (regression line and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

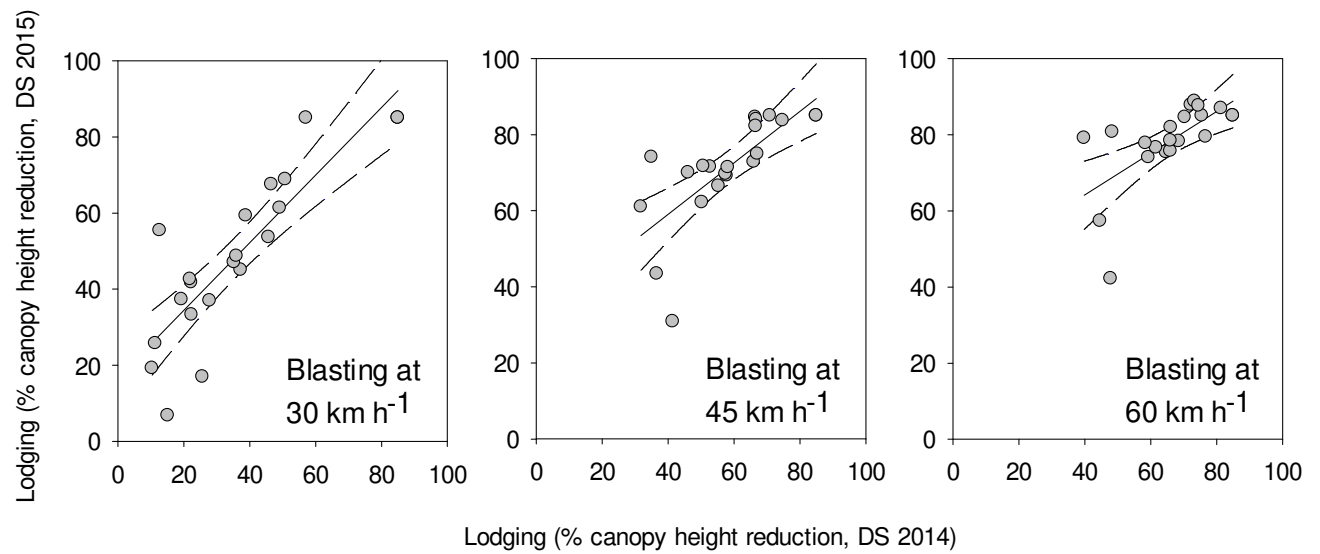
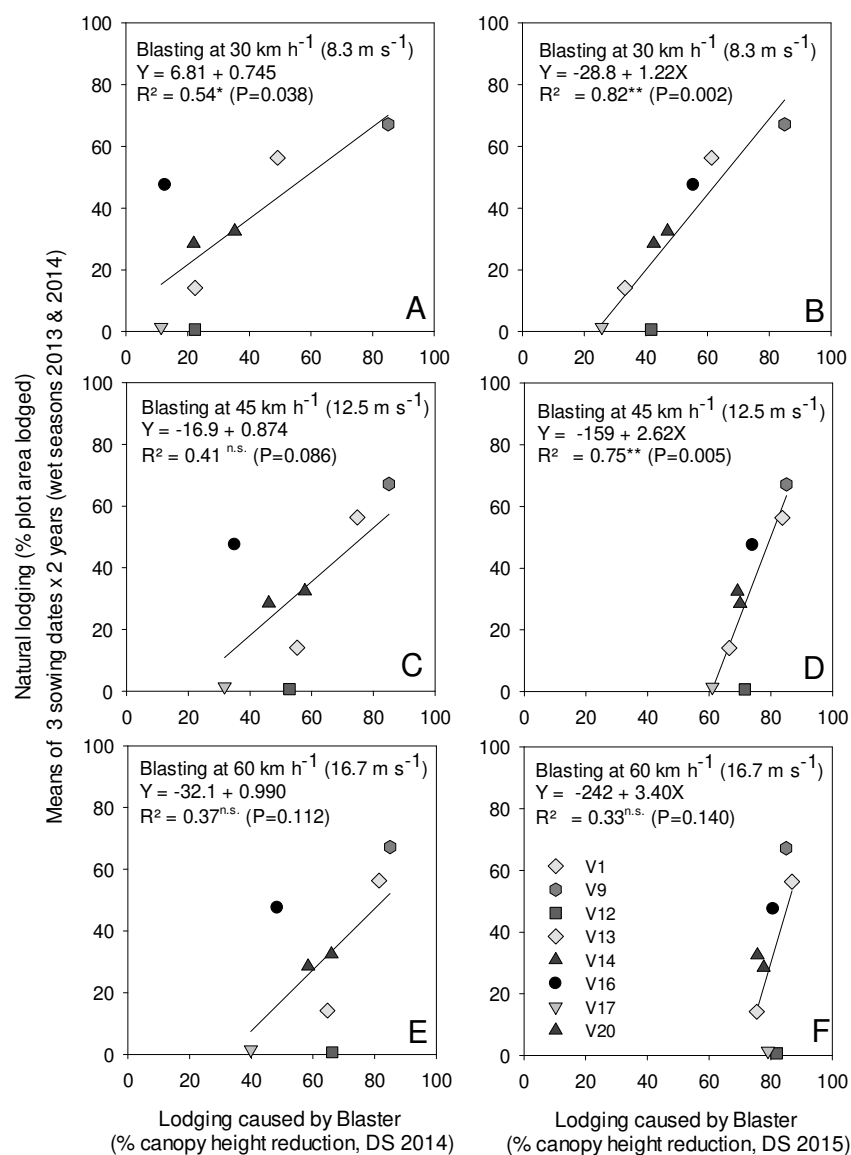


Fig. 5. Comparison of induced lodging results between DS 2014 and DS 2015 for the same genotypes and identical setup. Linear regression analyses: 30km/h : $Y=0.889X+16.6$, $R^2=0.733$, $P<0.0001$; 45km/h : $Y=0.677+31.94$, $R^2=0.541$, $P<0.001$; 60km/h : $Y=0.549X+42.25$, $R^2=0.420$, $P<0.01$.



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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.**

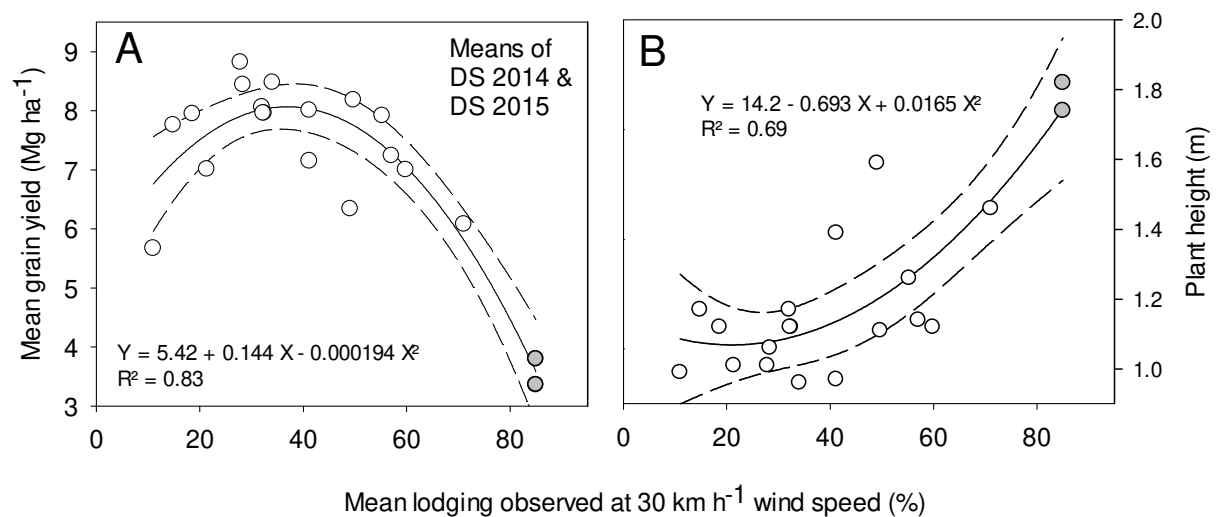


Fig. 7. Relationship between grain yield (A) and plant height (B) vs. lodging response at 30 km h^{-1} wind speed across 20 genotypes. All data are means for DS 2014 and DS 2015 experiments. Filled symbols indicate cases of spontaneous lodging occurring before Blaster treatment. Grain yields were measured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

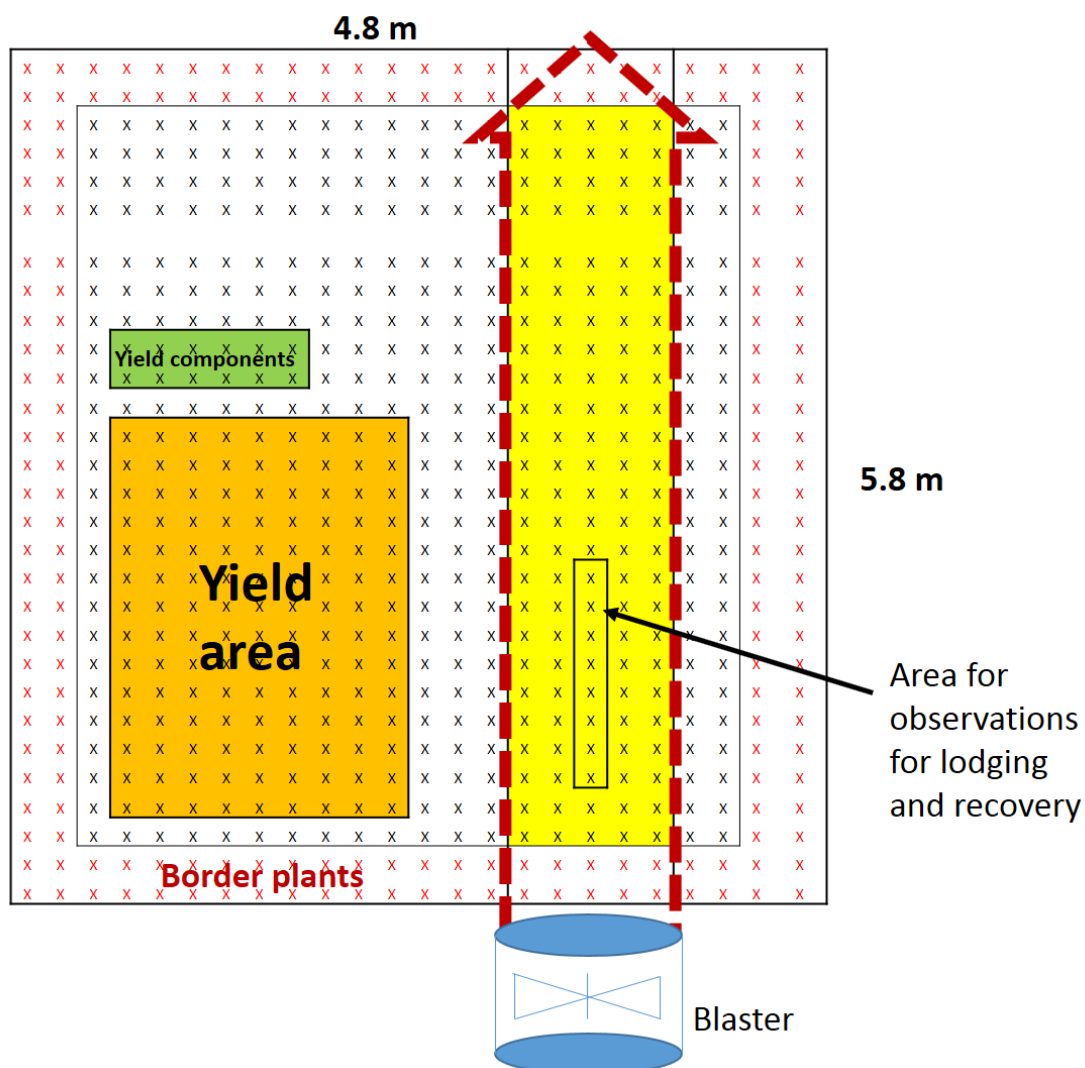
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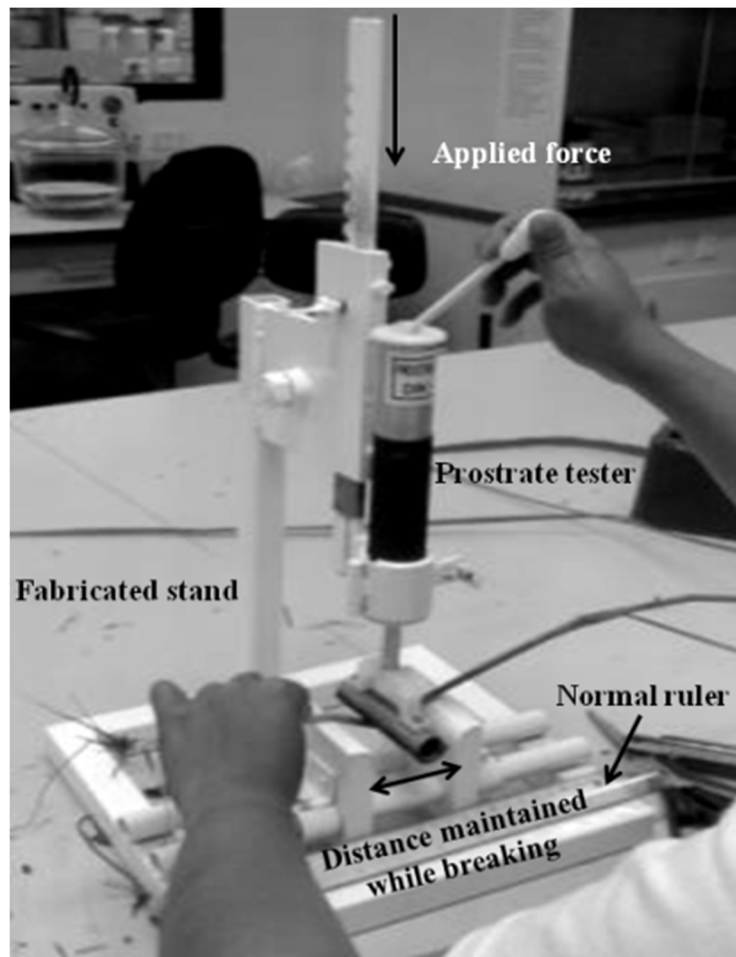
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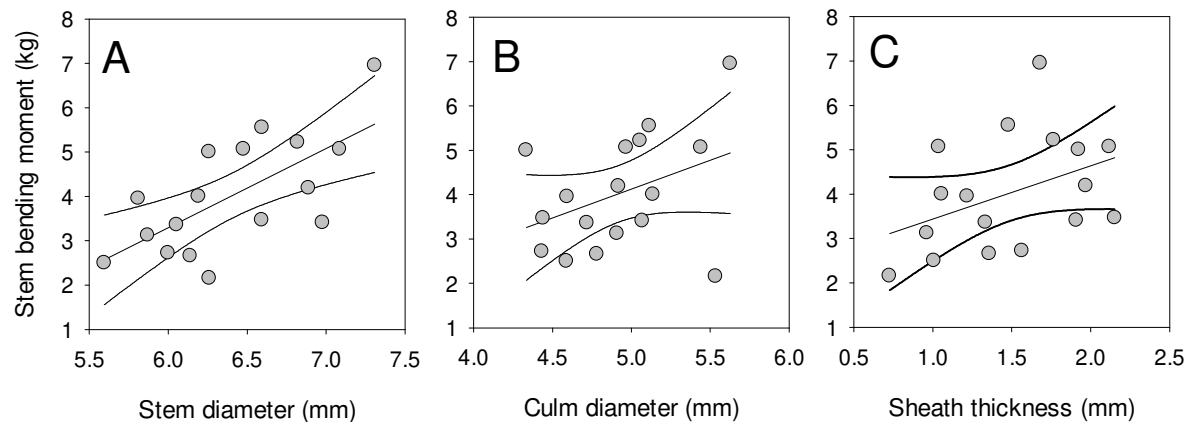
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759 **Supplemental Fig. S1. Experimental plot layout and locations of sampling.**

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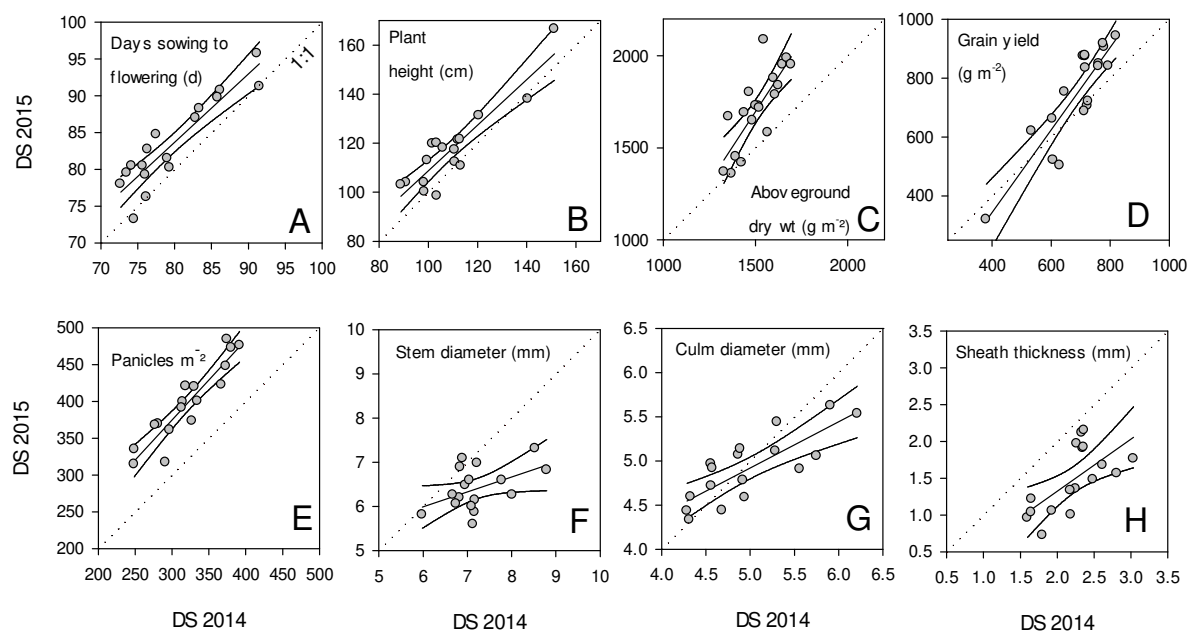


Supplemental Fig. S2. The load-testing device developed to measure stem bending moment at breakage.



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

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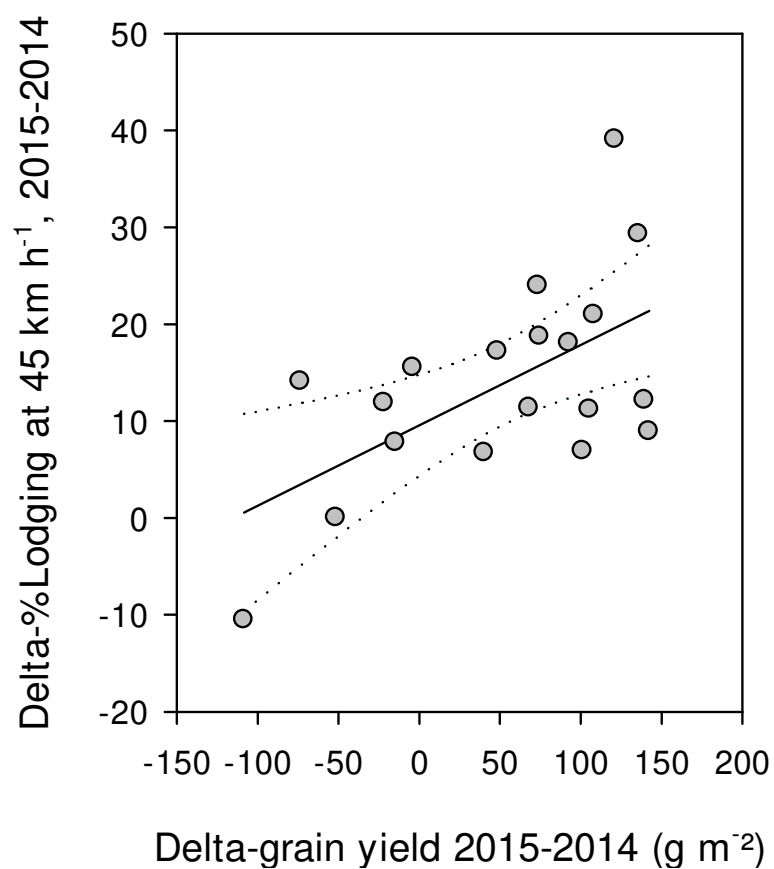


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776 **Fig. S4. Linear correlations for phenological and morphological crop traits between DS 2015 and DS**
 777 **2014.**

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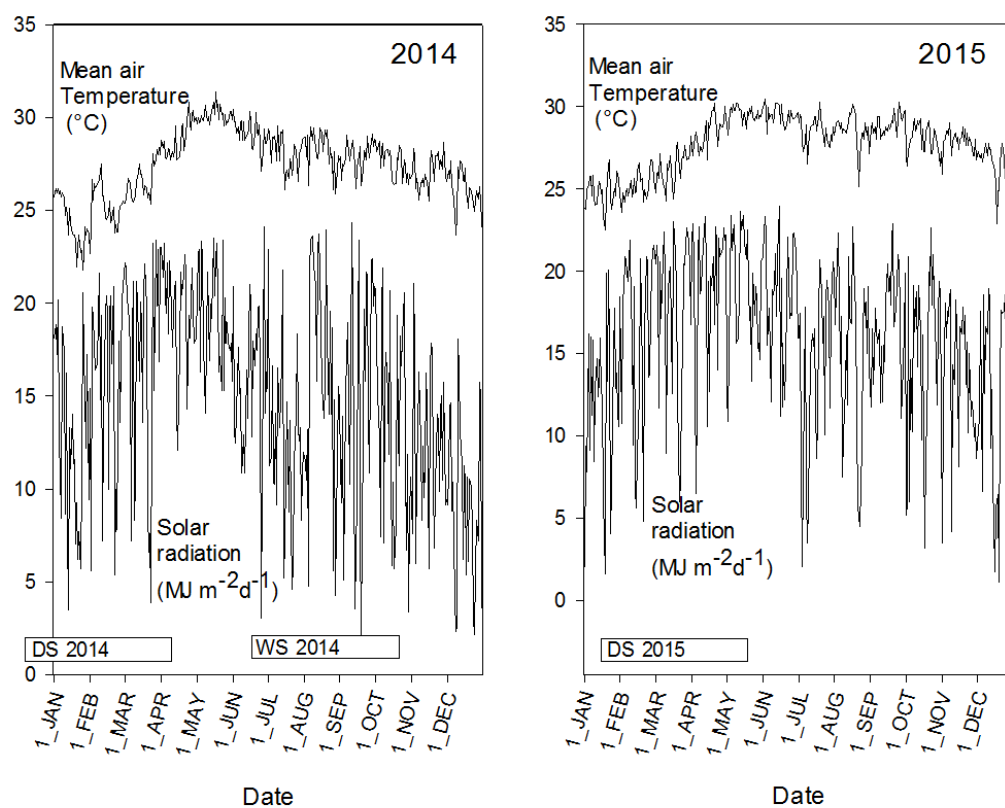
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782 **Supplemental Fig. S5. Relationship between the DS 2015-2014 annual difference in grain yield and**
 783 **the annual difference in induced lodging at 45 km h⁻¹ in the dry season. Correlation:**

784 **$Y=9.55+0.083X$, $R^2=0.35$, $P<0.01$**

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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**



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