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THE TRAITS DETERMINING PLANT LODGING AND ASSESSMENT OF LODGING RESISTANCE IN INTENSIVE AND EXTENSIVE RUSSIAN RICE (*Oryza sativa* L.) VARIETIES

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Abstract

Lodging is one of the main causes of rice crop loss due to adverse effects on photosynthesis and plant productivity. Plant bend hinders illumination and makes it difficult for the plastic substances to flow out of the stem and leaves to the panicle. This worsens grain filling, technological and sowing qualities. Lodging restricts potential productivity of rice varieties. The resistance of a variety to lodging depends on its genotype, the strength of the stem tissues, and the growing conditions. Insufficient stability of rice plant stems occurs when the crops are thickened or subjected to high nitrogen supply, deep water in the rice field, increasing dynamic loads due to sprouting, wind, rain, dew and diseases. The objective of this study was to determine morphophysiological traits causing resistance to lodging of rice (*Oryza sativa* L.) intensive and extensive varieties with a focus on th use of laboratory method for express estimates of lodging resistance. The studied Russian rice varieties were Rapan, Vizit, Gamma of intensive type and Sonata and Atlant of extensive type. Plants grew in concrete micro-check plots filled with soil from rice check plots in which rice irrigation mode was the same as in field conditions. The fertilizers, as ammonium sulphate, superphosphate and potassium chloride, were applied at $N_{24}P_{12}K_{12}$ and $N_{36}P_{18}K_{18}$ dosages. The study showed that during tillering to booting of intensive varieties Rapan, Vizit, Gamma, photosynthesis assimilates are more used for the formation of generative organs and less vegetative, resulting in high productivity of panicle, but less lodging resistance. Varieties of extensive types, Sonata and Atlant, during tillering—booting period use more for stem formation and less for panicle productivity elements formation. This leads to a decrease in panicle productivity and yield, while the resistance of sowings to lodging increases due to higher strength of the lower internodes. To quantitate lodging resistance of rice varieties, we measured mechanical resistance of lower part of stem, including the first and the second culm internode, to bend. This index averages 56-63 g for the intensive varieties, 66-80 g for extensive varieties 66-80 g, and correlates with lodging rate of tested genotypes under field conditions at $r = -0.99$ ($p \le 0.050$). The increase in cellulose content per unit stem length and lower internodes resistance are the main traits for reducing the lodging of rice plants.

Keywords: *Oryza sativa* L., rice, intensive varieties, extensive varieties, panicle productivity, lodging resistance, cellulose, bending resistance, yield

Rice (*Oryza sativa* L.) is one of the most widely consumed staple foods for a large part of the world's human population. As of 2014-2015, the rice planting area in 116 countries was 160 mln hectares with yearly output about 740 mln tons, to be 781 mln tons by 2020 according to FAO forecasts (keeping the planted area) thereby exceeding 2-3 % demand for wheat [1, 2]. In 2018, the State Register for Selection Achievements to be applied was amended with 57 rice varieties, including 31 varieties being selections of All-Russian Rice Research Institute. Meeting the increasing demands in current climatic changes is due to highly efficient technologies and varieties [3-5] with improved biotic and abiotic stress tolerance, quality and productivity [6, 7]. Potential rice yield has significantly increased after the “green revolution” through appearance of semi-dwarf varieties (1950s), three-way cross hybrids (1970s) and superhybrid rice (1996) [8, 9] with powerful heterosis [10] and improved donor-acceptor bonding [11], thereby enabling extra 12 % rise in the yield as compared with usual hybrids and inbred varieties of this crop. Besides, super-rice cultivation technology was improved [10].

Lodging is one of causes reducing productivity of the majority of cereals, sometimes resulting in productivity reducing almost twice especially with high-yielding rice variety [12-15]. Excessive nitrogen application, high density of planting, and global warming are demonstrated to result in lodging [16]. Heavy lodging is reducing transpiration, transport of nutrients and assimilants through xylem and phloem thereby reducing using thereof at grain-filling [17]. Besides, the lodged plant leaves may become favorable environment for diseases affecting the crop and grain quality because of high humidity [18].

Dwarfing genes were introduced into wheat and rice varieties to reduce plant height for better lodging resistance and crop yield [19-21]. However, low height may decrease photosynthetic activity and biomass of plant stands [22, 23]. Reducing the plant height by 6 cm is resulting in reduction of potential yield by 1 t/ha [24]. The analysis made has confirmed competitive connections between potential yield and lodging resistance. This problem in rice cultivation is partially solved by applying growth regulators and retardants [25, 26].

Strength of cereal stem is defined first of all by morphological characters and anatomic plant structure, with the latter being the result of growth and development at the cellular level and depends on environmental effects [27]. Shadowing of the corn results in reducing of the mechanical tissue thickness, amount of vascular bundles, xylem and phloem area [28], morphoanatomical changes are accompanied by high stem fragility [29]; longer and slender stem with lower density of tissue is formed in wheat at high density of crop thereby affecting lodging resistance [30]. Rice and wheat with high stability of stems and lodging resistance are characterized by larger outer diameter, stem wall and mechanical tissue thickness, large amount of big and small vascular bundles [31, 32]. However, A. Kelbert et al. [33] claims that thickness of extraxylary tissue of wheat varieties is not connected with resistance to lodging. Stem fracture strength, weight of the 2nd low internode, weight of grain in the main spike or plant are shown to be reducing at lodging of winter rye plants. Variability of these characteristics is largely due to degree of lodging than genotype. These characteristics are recommended to be used as selection criteria to evaluate resistance to lodging because of strong conjugation between elements of productivity, morpho-anatomical, dynamic stem features and degree of lodging thereof [34, 35].

Optimum nitrogen application is increasing rice yield [36, 37], but excessive application thereof may result in lodging [38, 39]. High nitrogen quantities reduce lodging resistance of rice and wheat by increasing a number of shoots, length of low internodes, plant height, reducing the dry weight per 1 cm of stem [40, 41]. The lodging is shown to be reduced by applying less nitrogen, i.e. risk of rice lodging proves to be low at average rate of nitrogen consumption [42-44].

To make selection of new high-yielding varieties considering anatomic and biochemical features of rice plants one should get such data from original parents and hybrid progeny thereof [13, 14]. Data on anatomic inherited features defining degree of lodging [45, 46] and variability thereof in hybrids of the first and next generations are also required. Additionally simple and informative methods for analyzing both anatomic and biochemical features of rice plants are to be applied.

Morphophysiological traits causing greater lodging of Russian intensive and extensive varieties of rice depending on nitrogen status were originally demonstrated herein. The resistance is stipulated by low cellulose content in stems and, thereby weak mechanical bend strength thereof. Rice samples were assessed to lodging by loading causing stem bending closely connected with degree of lodging.

The objective of this paper was to analyze morphophysiological traits causing resistance to lodging of intensive and extensive varieties of rice (*Oryza sativa* L.).

Techniques. Micro-plot experiments were made in 2012-2015 [47]. Russian rice varieties Rapan, Vizit, Gamma (intensive type) and Sonata and Atlant (extensive type) were compared. The experiments were made in reinforced concrete tanks maintaining irrigation schedule typical to field conditions, with planting taking place on May, 5-7, and harvesting on September 1-5. The tank (3.6 m^2) was filled with meadow chernozem soil taken from rice irrigation system of All-Russian Rice Research Institute. Inorganic nutrition status are $N_{24}P_{12}K_{12}$ (optimum) and $N_{36}P_{18}K_{18}$ (high) (per 1 m^2). The plot area in the experiments was 1.2 m^2 with 3-fold replication. Density of plant crop is 300 per m^2.

Amount of shoots in certain plots was counted. During flowering period, the plants were taken to determine dry weight and weight of certain organs: leaves, stems and panicles. The crop area with lodged plants (as a percentage of total plants in the plot), with stem resistance to bend and content of cellulose in tissue thereof as well as crop yield, were considered [48] during full grain maturity stage. Stem strength was measured on day 28 of flowering start. Main shoots (by 10) were taken in 3-fold replication, with the low part (12 cm) including 1st and 2nd culm internodes cutting off, with no leaves on. Low part of the sample was support-fixed horizontally, the free end thereof being 30° bent using weight set and calculating weight of loading. Mean value thereof was calculated for assessing correlation with resistance to lodging.

The results were subjected to two-way ANOVA and regression analysis, arithmetical mean (*M*) and standard error of the mean (±SEM) were calculated with Doc Statpak program [49]. Statistical significance was found by Student's *t*-test, the results were considered significant at $p \leq 0.05$.

Results. Temperature conditions in the analyzing years were similar to long-time average annual values. The starting period with average temperature above 10 °C was May 7-18, the ending period was September 17-30, length being 122-146 days, sum of positive temperatures was 2,300-3,000 °C. Deviation from average monthly temperature in July did not exceed 2.0-3.5 °C.

Plant lodging of all analyzed varieties was seen under both optimum and high nutrient status, in Rapan and Gamma varieties being extremely high in the latter case. It should be noted that plant height has no statistically significant connection with the degree of lodging [50]. Varying resistance to lodging occurs as a result of unequal intensity of biosynthesis of gibberellins and auxins when applying average and high amount of nitrogen fertilizers.

Cellulose is the main component of cell walls and fiber vascular bundles responsible for the strength of skeletal tissues of the culm. In thick planting and at high nitrogen application the biosynthesis thereof is weakened thereby resulting in less cellulose in stems [51]. The amount thereof in the unit of stem length was decreasing under such conditions due to enhanced cell extension lengthwise against crosswise size thereof [52]. Changes in cellulose content in stems were accompanied by plant lodging. Various resistance of rice varieties to lodging, first, was due to unequal cellulose content in stems to be defined by genotype and, second, unequal response to excessive nitrogenous nutrition (Table 1).

1. Content of cellulose in stems, resistance to bend and degree of lodging in rice (*Oryza sativa* L.) varieties at full maturity depending on inorganic nutrition dosage (*M*±SEM, 2012-2015)

Variety	Type	Cellulose, %	Cellulose per 1 cm stem length, mg/cm	Stem resistance to bend, g	Lodging, %
			$N_{24}P_{12}K_{12}$		
Rapan	I	31.27±0.58	4.45±0.05	60.00±0.71	43,30±2,35
Vizit	I	30.89±0.57	4.55±0.05	62.50±0.75	36,70±2,36
Gamma	I	29.70±0.55	4.79±0.05	60.00±0.73	40,00±2,04
Sonata	II	31.87±0.86	5.85±0.06	79.80±1.18	1,00±0,04
Atlant	II	32.40±0.87	5.01±0.06	73.80±0.90	13,30±0,95
r with degree of lodging		–0,70±0,25	–0.92±0.22	–0.99±0.04	
			$N_{36}P_{18}K_{18}$		
Rapan	I	28.41±0.54	4.19±0.04	56.20±0.88	53,30±2,39
Vizit	I	33.36±0.88	4.43±0.05	58.80±0.90	43,30±1,69
Gamma	I	29.40±0.55	4.40±0.05	57.50±0.95	50,00±2,04
Sonata	II	29.49±0.56	5.06±0.06	72.30±1.17	6,70±0,28
Atlant	II	29.01±0.53	4.50±0.06	66.40±0.91	23,30±1,67
r with degree of lodging		0,10±0,57*	–0.92±0.23	-0.99±0.03	
LSD_{05}		1,67	0.17	3.4	3.27

N o t e. I is intensive, and II is extensive variety; *r* — correlation coefficient.
* Unreliable value; other correlation coefficient values are statistically significant at $p \leq 0.05$.

Content of cellulose in stems of intensive Rapan, Vizit and Gamma varieties at $N_{24}P_{12}K_{12}$ dosage was much lower than in Sonata and Atlant varieties. And high concentration thereof at $N_{36}P_{18}K_{18}$ dosage was found in Vizit variety. Plant lodging took place at cellulose concentration in stem less than 4.8 mg for optimum nitrogen application, and less than 4.5 mg for high application. Close feedback was identified between amount of cellulose per 1 cm of stem length and rice plant lodging (*r* from –0.92 ±0.22 to –0.92 ±0.23): the less is the cellulose concentration per 1 cm of stem length, the higher is the lodging under other equal conditions.

Growing of varieties combining productivity and resistance to unfavorable conditions is a complicated problem, especially when it deals with yield enhancement closely connected with improvement of donor-acceptor relations combining spectrum of morphophysiological biometric traits being the basic models for both intensive and extensive rice varieties.

Mechanisms responsible for lodging resistance during plant maturation period deal with less number of morphophysiological traits. Importance of these mechanisms in the course of rice yield enhancement is great: incomplete realization of potential productivity in cultivated varieties is often seen due to insufficient density of crop and lodging during kernel filling [52].

Plant stems and panicles affecting coenosis resistance to lodging are formed during tillering-booting period. These processes continue in flowering period. Weight of stems and panicles of the analyzed varieties in this period was differed greatly due to various intensity of assimilant input (Table 2). The intensive varieties used less assimilants for stem formation and share thereof in shoot weight, while the extensive ones used more assimilants thereby increasing resistance to lodging thereof. This resulted in increase of carpophore productivity and crop in the intensive varieties but in less resistance to lodging.

Sonata and Atlant varieties were forming stems with resistance to bend but with less panicle productivity. We have found the connection of lodging with the weight of stem and panicle, as well as yield (see Table 2) thereby enabling to assess rice genotypes by these traits to find the promising forms.

2. Stem and panicle weight at flowering, degree of lodging and yield of rice (*Oryza sativa* L.) varieties depending on inorganic nutrition dosage (2012-2015)

Variety	Type	Lodging, %	Stem weight		Panicle weight		Yield, kg/m^2
			g	percent of shoot weight	g	percent of shoot weight	
				$N_{24}P_{12}K_{12}$			
Rapan	I	43.30±2.35	1.59±0.03	62.60±0.25	0.40±0.01	15,75±0,32	1,206±0,030
Vizit	I	36.70±2.36	1.49±0.03	63.14±0.30	0.33±0.01	13,98±0,33	1,078±0,020
Gamma	I	40.00±2.04	1.34±0.02	59.00±0.32	0.35±0.01	15,42±0,35	1,058±0,020
Sonata	II	1.00±0.04	1.64±0.04	67.77±0.33	0.32±0.01	13,22±0,31	0,994±0,020
Atlant	II	13.30±0.95	1.95±0.04	67.71±0.34	0.32±0.01	11,11±0,28	0,933±0,010
r with degree of lodging			–0,56±0,23	–0.88±0.27	0.71±0.20	0.71±0.19	0.700±0.190
				$N_{36}P_{18}K_{18}$			
Rapan	I	53.30±2.39	1.55±0.03	60.31±0.32	0.40±0.01	15,56±0,32	1,264±0,050
Vizit	I	43.30±1.69	1.67±0.04	66.80±0.33	0.31±0.01	12,40±0,29	1,207±0,020
Gamma	I	50.00±2.04	1.24±0.02	60.50±0.32	0.27±0.01	13,17±0,31	1,107±0,020
Sonata	II	6.70±0.28	1.69±0.04	67.06±0.35	0.32±0.01	12,70±0,32	1,098±0,020
Atlant	II	23.30±1.67	2.05±0.05	69.49±0.36	0.34±0.01	11,53±0,33	0,940±0,010
r с полегаемостью посевов			–0,55±0,23	–0.73±0.19	0.10±0.58*	0.53±0.23	0.600±0.220
LSD_{05}		3,27	0,08	1.72	0.02	0.52	0.05

N o t e. I is intensive, and II is extensive variety; *r* — correlation coefficient.
* Unreliable value; other correlation coefficient values are statistically significant at $p \leq 0.05$.

Bending strength value was to 73.8-79.8 g in Atlant and Sonata extensive varieties, while 60.0-62.5 g in Rapan, Vizit and Gamma intensive varieties at optimum nitrogenous nutrition (see Table 1). The value for the first two varieties decreased to 66.4-72.3 g, while for the others to 56.2-58.5 g at high nitrogene nutrition. Therefore, variety differences in bending strength also remained the same at providing the plants with extra nitrogene nutrition. We found strong negative dependence between amount of load and degree of lodging (*r* from –0.99 ±0.04 to –0.99 ±0.03). It should be mentioned that the applied express assessment of resistance of low parts of stems to bend is quite simple and reliable revealing high efficiency for the last ten years as compared with labor-intensive analysis for cellulose concentration in rice stems.

Formation of varieties increased production is stipulated by efficient utilization of photosynthesis assimilants and plant reserve constituents for making grain yield [52, 53]. Higher macronutrients inflow to the panicle being formed is seen in high-yielding rice varieties thereby forming more spikelets and complete kernels defining higher yield of these genotypes, and resistance thereof to lodging is declining therewith [52]. Assimilants in intensive varieties are largely used for making vegetative organs, and for panicle productivity elements, to a lesser extent which results in better resistance of plants to lodging. In other words, assimilant distribution pattern along shoot organs is responsible for making morphological and physiological traits defining both amount of the yield and resistance to lodging.

We have noted the differences by resistance to lodging in various varieties analyzed due to unequal cellulose content in stems stipulated genotypically, depending therewith on varieties response to nitrogen supernutrition. Therefore, one of the approaches to control productivity and rice resistance to lodging (both on the genotype level and by agrotechnology optimization) may be based on cellulose content in stems [15, 51, 52]. The increase in cellulose content per stem length and lower internodes resistance are the main traits for reducing the lodging of rice plants. The analyzed role of nitrogene nutrition in rice resistance to lodging and relation thereof with productivity on the whole agree with other authors' reports [40, 42-44].

Therefore, susceptibility of rice plants to lodging is stipulated by cellulose accumulation in the stem that may be assessed by the mechanical resistance thereof to bend. Such resistance including the one dealing with the response to nitrogene nutrition level is unequal in the analyzed varieties. The prevailing part of photosynthesis assimilants is used by intensive varieties for forming high-yielding panicle defining productivity of genotype and agrophytocenoses, but resistance to lodging thereof is declining therewith. Stems with more resistance to bend but with less panicle productivity are formed in extensive varieties. These features are to be considered in rice selection programs for productivity and resistance to lodging.

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