Construction of a mathematical model of cereal lodging

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Abstract. The increase in the yield of cereals - the main food product of the world's population - is the result of a modern approach to the process of growing and harvesting, the introduction of new methods of breeding work based on methods of mathematical modeling. Lodging of crops leads to significant crop losses. The article describes the methods developed by us for determining the physicomechanical properties and architectonics of plants, which are used to construct a lodging model. The study was carried out using mathematical analysis and methods of technical mechanics to find the features of resistance to lodging of stems of winter and spring cereals, depending on the variety and species. The physicomechanical properties of their tissues and the parameters of the architectonics of cereal plants were determined, which are recommended to be used when breeding new varieties and hybrids that are resistant to lodging.

1. Introduction

Crops undergo numerous challenges from germination to harvest. One of the most dangerous is lodging, which can lead to large-scale losses of both grain and its quality, as well as big problems during harvesting (Figure 1).

Figure 1. Field of lodged barley.

There are two forms of lodging: root and stem. In general, lodging is the displacement of stems or roots from their vertical placement as a result of exposure to wind, rain or dew, which weaken the strength of the plant root in the soil and the density of the stem tissue [1]. Lodging also increases the
susceptibility of plants to pests and diseases [2], which has a negative impact on the development of the crop (decrease in grain per m2 and average grain weight). Lodging affects all types of cereals and many other crops such as oilseeds.

Breeding can reduce these losses by creating a plant of reduced height (mainly due to introgression of dwarf genes) [3]. Plants with a strong, sturdy stem, that is, with an increased diameter of the bases of the stems with thick walls, can also be obtained by reducing the seeding rate or applying a lower amount of nitrogen [4].

It is well known that attempts to increase the yield by increasing doses of organic and mineral fertilizers, large investments in the creation of irrigation systems and other large reclamation measures aimed at improving the general agricultural background, very often do not achieve the desired results and are not economically justified [5, 6]. Only a variety that is resistant to lodging along with other economically valuable traits can meet the increasing demands of modern agriculture. A favorable combination of morphological, anatomical, physiological and biochemical properties in a variety determines its resistance to lodging and the associated increase in yield in certain soil and climatic conditions [7, 8, 9].

In solving the problem of realizing the biological potential of cereal in the plant community, an important place is occupied by studies of the lodging phenomenon [10-13]. Physiologists are unanimous in the opinion that lodging is a reaction to growth conditions [14].

For a long time, researchers have tried to describe the behavior of the stem as an elastic rod in terms of mathematics and technical mechanics. Such problems remain poorly understood, despite their importance for many biological processes.

The first studies of the stability of forms of equilibrium of elastic systems were carried out in 1490-1505. Leonardo da Vinci. Significant results of his experimental research are noted in the works of F.S. Yasinsky and S.P. Tymoshenko [15].

In 1594-1609, G. Galilei carried out experimental studies of the bending of elastic beams. His treatise "On the Science of Mechanics" played an outstanding role in the dissemination of the scientific foundations for calculating elastic rods and beams in bending.

In 1678, R. Hooke's book "On the restorative capacity or on elasticity" was published, which presents the results of experiments on determining the elastic deformations of various materials, including tree trunks [16].

In the years 1666-1684, the buckling of beams was studied by Marriott. In addition to the experimental study of the bending of beams under various conditions for fixing the ends, Mariotte theoretically considered many questions of the mechanics of elastic bodies, taking into account the laws established by the experiments of R. Hooke [17].

The experimental results of P. Muschenbrook were well known to D. Bernoulli, who was engaged in the development of the theoretical foundations for calculating the transverse bending of rods. In 1751 D. Bernoulli obtained a differential equation describing the transverse vibrations of a prismatic bar. In 1735-1739, in letters to L. Euler, D. Bernoulli reports on the possibility of applying the calculus of variations to solving problems in the theory of bending of elastic columns.

L. Euler in 1740 conducts a study of the form of equilibrium of elastic columns. In 1744, L. Euler's book [8] on the calculus of variations was published, where the theory of bending of elastic columns was presented. Using the calculus of variations, L. Euler was the first to obtain an exact differential equation for the bending of a thin elastic rod under the action of an axial compressive force. The somewhat specific conditions adopted by L. Euler in solving the problem of the bending of an elastic column and the method of studying stability itself could not be understood by many for a long time, therefore, the theory of buckling until the end of the seventeenth century was a little developed field of mechanics. However, L. Euler himself repeatedly addressed the problem of the bending of elastic columns.
2. Materials and methods
In order to determine the physicomechanical properties and parameters of plant architectonics, we carried out long-term observations and experiments (1997–2020).

The research was carried out on experimental fields in the educational farm "Kuban" of the FSBEI HE KubSAU named after I. T. Trubilina, Federal State Budgetary Scientific Institution "Scientific Center of Plant named after P. P. Lukyanenko", Federal State Budgetary Scientific Institution "Federal Scientific Center of RISA", the soils of which correspond to the southern climatic zone of the Krasnodar Territory. Bamboo plants of the genus phyllostachis were grown in natural conditions in Sochi.

The soils of the zone are represented by the Western Ciscaucasian low-leached and leached low-humus chernozems. The climate of the zone is moderately mild. The meteorological conditions during the years of the experiments were close to the multiyear norm.

In the experiments, urea, ammonium nitrate, double superphosphate, and potassium chloride were used, which were introduced in standard doses.

Experimental plants of 10 varieties of winter and spring wheat, triticale, winter and spring barley, sorghum, 10 hybrids of corn, 4 varieties of rye, rice were harvested manually, randomly, during the growing season, dangerous from the point of view of lodging: flowering, milky wax and full ripeness.

In total, 19700 measurements of stem deflections were made on a specially designed laboratory setup with a varying shear force for wheat plants; 2700 measurements of stem deflections were made for rye plants; 9000 measurements of stem deflection were made for triticale plants; 18000 measurements of stem deflections were made for barley plants; 8100 measurements of stem deflections were made for maize plants; 3600 measurements of stem deflections were made for sorghum plants; 2500 measurements of stem deflection were made for bamboo plants; for rice plants, 2824 measurements of stem deflection were made (Figure 2).

Measurements "stress - deformation" were carried out at a distance between the clamps of the tripods 0.2-1.0 m, i.e., there is no scale effect. The repetition rate of experiments is from three to ten. The stem is hinged. A thread was pulled between the tripod clamps. The deflection of the stem sample in the middle of the relatively taut thread was measured with a caliper with millimeter accuracy. The number of loads - 10-20 - in the middle of the stem sample was carried out with weights with a step from 0.1-0.2 N to 20-40 N.

Samples were cut from various parts of the stem; the diameters of its ends were measured with a caliper with an accuracy of tenths of a millimeter.

The formulas for calculating the diameters of the stem sample are as follows:

\[ D = \sqrt[4]{0.5(D_1^4 + D_2^4)} \]
\[ d = \sqrt[4]{0.5(d_1^4 + d_2^4)} \]

where \( D_1, d_1 \) и \( D_2, d_2 \) – average outer (D) and inner (d) diameters of the stem ends sample.
Figure 2. Installation for determining the deflection of the stem sample: 1 – stands; 2 – legs; 3 – cargo; 4 – stem sample; 5 – thread; 6 – table; \( f \) – deflection of the stem sample in the middle under the action of the force \( P \).

As a result, stress-strain diagrams were built for all crops, all varieties and hybrids in three phases of the growing season (Figure 3). Young’s modulus, elasticity and yield limits were determined from the diagrams.

3. Results and discussion

As a result of the analysis of the constructed diagrams "stress-strain" for all studied crops and varieties in three phases of the growing season, a scheme for determining the parameters of the resistance of cereal plants to lodging was drawn up (Table 1).

The methods of mathematical modeling and technical mechanics used explain the ability of plants of all studied cereals (except for corn and rice) to maintain the integrity of the stem when bent under the influence of unfavorable natural factors (wind, rain, dew, etc.).

Numerous measurements revealed the following regularities: the length of the plant stem changes from the smallest (in spring barley - 53 cm) to the largest in corn - 187 cm, the outer diameters at the root change, respectively, from the smallest in spring wheat (2.5 mm) to the largest (24, 0 mm) in maize.

We have established the ability of wet plants of corn, rice and sorghum (as opposed to barley, wheat, rye, triticale) to maintain vertical stability under the existing parameters of architectonics.
The necessary numerical changes in the architectonics for maintaining the vertical stability of plants have been determined. For winter wheat, this is an increase in the diameter at the ear by 8 - 33% and a decrease in the length of the stem by 12 - 21%. For spring wheat - an increase in the ear diameter by 24 - 50%, a decrease in the stem length by 24 - 41%; For rye - an increase in the ear diameter by 40 - 37%, a decrease in the stem length by 48 - 36%. For triticale - an increase in the diameter at the ear by 10 - 19%, a decrease in the length of the stem by 19 - 26%. For winter barley - an increase in ear diameter by 19 - 40%, a decrease in stem length by 30 - 38%. For spring barley - an increase in the diameter of the ear by 32 - 57%, a decrease in the length of the stem by 33 - 40%. For corn - 50% increase in stalk weight with cobs. For rice - an increase in panicle mass by 50% with a simultaneous increase in the diameter of the panicle stem by 9 - 12% and a decrease in the stem length by 15 - 11%.

Table 1. Algorithm for selecting the optimal parameters of resistance to lodging of cereal plants.

Abbreviations: L – stem length, D0 – outer diameter of the stem at the root, D – outer diameter of the stem at the ear (panicle).

| Winter wheat | Spring wheat | Rye | Triticale | Winter barley | Spring barley | Corn | Rice | Sorghum |
|--------------|--------------|-----|-----------|---------------|---------------|------|------|---------|
| L = 73 – 106 cm; D₀ = 3.7 – 4.0 mm | L = 56 – 83 cm; D₀ = 2.5 – 2.8 mm | L = 133 – 148 cm; D₀ = 4.3 – 4.7 mm | L = 92 – 123 cm; D₀ = 5.1 – 5.3 mm | L = 70 – 106 cm; D₀ = 4.1 – 4.3 mm | L = 53 – 73 cm; D₀ = 2.8 – 3.0 mm | L = 170 – 187 cm; D₀ = 23.6 – 24.0 mm | L = 82 – 89 cm; D₀ = 7.7 – 8.1 mm | L = 78 – 168 cm; D₀ = 13.2 – 15.3 mm |

Maintaining vertical stability with the existing parameters of architectonics in adverse weather conditions (wind, rain, dew)

| Winter wheat | Spring wheat | Rye | Triticale | Winter barley | Spring barley | Corn | Rice | Sorghum |
|--------------|--------------|-----|-----------|---------------|---------------|------|------|---------|
| No | No | No | No | No | No | Yes | Yes | Yes |

Necessary changes in architectonics to maintain vertical stability of plants

- Increase D by 8 – 33%
- Decrease L by 12 – 21%
- Increase D by 24 – 50%
- Decrease L by 24 – 41%
- Increase D by 40 – 37%
- Decrease L by 48 – 36%
- Increase D by 10 – 19%
- Decrease L by 19 – 26%
- Increase D by 19 – 40%
- Decrease L by 30 – 38%
- Increase D by 32 – 57%
- Decrease L by 33 – 40%
- No, you can additionally increase the weight of the stalk with ears by 50%
- No, with an increase in the mass of the panicle by 50%, you need increase D by 9 - 12%, decrease L by 15 - 11%
- No, with an increase in the mass of the panicle by 50%, you need increase D by 4 - 9%, reduce L by 17 - 28%

Maintaining the integrity of the stem during bending of plants with optimal parameters of architectonics under the action of maximum wind loads

| Winter wheat | Spring wheat | Rye | Triticale | Winter barley | Spring barley | Corn | Rice | Sorghum |
|--------------|--------------|-----|-----------|---------------|---------------|------|------|---------|
| Yes | Yes | Yes | Yes | Yes | Yes | No | No | Yes |

Necessary changes in the architectonics and strength of stems to maintain plant resistance to lodging

- Increase D by 10%
- Increase in 1.4 - 1.5 times the elastic limit
- No

Table 1 shows that, for example, to increase the panicle mass of medium-sized and long-stemmed sorghum varieties by 50%, the stem length should be reduced by 17 - 28%, increasing the panicle stem diameter by 4 - 9%.
To maintain resistance to lodging, it is necessary to increase the stem diameter at the root by 10% for maize, and to increase the yield strength of the stem tissue by a factor of 1.4 - 1.5 for rice.

We have determined, depending on the growing season, the changing values of Young's modulus, the limits of elasticity and fluidity of the tissues of the stems of cereal plants.

Young's modulus: for rice - 1250 MPa, for corn, triticale, barley, wheat 1865-2243 MPa, for rye and sorghum 2915-3022 MPa and for bamboo 14722 MPa. Note that Young's modulus for beech wood is 12200 MPa and for larch its value is 14000 MPa, this is 14 times less than this indicator for low-grade steel, its Young's modulus is 200000 MPa (Figure 5).

Elastic limits: for rice - 4.4 MPa, for triticale, barley, corn, wheat 13.3-17.7 MPa, for rye, sorghum 19.1-22.7 MPa, for bamboo - 112.2 MPa. The found values are higher than the values of the elastic limit of beech wood - 95.3 MPa, larch - 98.7 MPa, 1.8 times less than this indicator for low-grade steel, its elastic limit is 200 MPa.

The yield points for vegetation phases: for rice - 6.6 MPa, for triticale, barley, corn, wheat, rye - 16.1-25.8 MPa, sorghum - 30.4 MPa, for bamboo - 138.7 MPa.

![Graph showing elastic limits and yield points for different types of plants.](image)

**Figure 4.** Physical and mechanical properties of cereal plant stem tissue averaged over the growing season.

### 4. Conclusion

Over the years of experiments with the plants of ten most important cereals, 82 contrasting varieties in three phases of the growing season, on various backgrounds of fertilizers, we have determined, using rigorous, scientifically grounded methods of mathematical modeling and technical mechanics, the most important indicators of the architectonics and physical and mechanical properties of these plants. Namely, statistically reliable numerical values of Young's moduli, elasticity and fluidity limits of plant stem tissues.

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