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Experimental study of the distribution of the heights of sugar beet root crowns above the soil surface

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Abstract. The results of experimental studies and operational tests of the sugar beet harvesting process carried out recently reveal that the latest models of beet harvesters produced in Europe and America cause considerable loss of the sugar-bearing mass. The source of this loss is mainly the poor topping of the crowns of standing sugar beet roots, more specifically the excessively low point at which the tops are cut off, which results in the straight out loss of sugar-bearing mass. Thus, there is need to search for such engineering solutions that would avoid both the loss of sugar-bearing mass and the presence of residual haulm on the roots. The aim of this study was to reduce the loss of sugar-bearing mass in the process of topping sugar beet root crowns. The results of this research into the distribution of the heights that root crowns protrude above the soil surface have confirmed the hypothesis that it follows the normal distribution. Based on the results, it has been established that this distribution has the following statistical parameters: mean deviation a = 20–30 mm, mathematical expectation m = 40...60 mm. The laboratory unit developed for this work and the field studies performed with it have provided sufficient evidence to develop a new system to automatically adjust the topping height on state-of-the-art root crop harvesters.

Key words: sugar beet, harvesting, loss, sugar-bearing mass, height control.

INTRODUCTION

Sugar beet growing is a strategic branch of the agricultural industry in the leading production states of Europe, America and China (Spiess & Diserens, 2001; Pidgeon et al., 2004; Gruber, 2005; Jansen & Stibbe, 2007; Wu et al., 2013). Harvesting is one of the critically important operations in the production of sugar beet, because at this stage a significant part of the crop can be lost (Khelemendik, 1996; Lammers & Schmittmann, 2013; Zang et al., 2013).

In view of the fact that root crop harvesting comprises the operations of topping the roots, lifting them and cleaning, the loss of harvested roots is determined by quite a number of factors (Smith et al., 1999; Bentini et al., 2005; Bulgakov et al., 2017). Emphasis should be placed on the most significant of these, which is the loss due to the unsatisfactory performance of the beet harvesters at the stages of topping the standing roots and the subsequent lifting of the roots out of the soil (Adamchuk et al., 2013; Zang et al., 2013; Bulgakov et al., 2016). An increase in the contamination by haulm waste in the sugar beet roots by just 1% over the accepted standard rate reduces the sugar recovery by 0.1%, while in the storage of roots in clamps prior to their processing, a haulm content of about 4% causes the daily loss of sugar to reach 0.02% (Bulgakov, 2013; 2016). In addition to that, sugar beet harvesters produced in Europe and America generate substantial loss of sugar-bearing mass from the excessively low shearing of root crowns (when a considerable part of the root crown which contain a large amount of sugar is cut off with the haulm).

Therefore, one of the current research options is to find ways to reduce the mentioned losses. There are many types of equipment designed to detect the root crown surface, but beet harvesters that perform topping without detectors have become the most common currently used equipment (Bulgakov et al., 2013). The current state-of-the-art sugar beet harvesters mostly employ rotor-type topping units, which cut off the tops of the roots at the same height relative to the soil surface. The selection of the height to cut off the tops is made following the generally accepted recommendations, but in practice they are often difficult to follow, in view of the probabilistic nature of the distribution of the height of top of the beets above the ground level, from which the root crowns protrude (Zhang et al., 2013). Despite that, users of the sugar beet harvesting machinery are always faced with the problem of selecting the appropriate height at which to shear the root crown under specific operational conditions. The different ways the root crowns protrude is important because that is what actually defines the crop yield index. In most cases, the problem is dealt with using rule-of-thumb methods (including visual assessment of the performance of the haulm gatherer following several trial runs). These might have to be repeated several times which is wasteful expenditure of work time, and consequently_reduces harvesting productivity, but does not guarantee a high level of accuracy in regard to harvesting the whole beet growing estate. Also, with this approach, it is possible to select the incorrect shear height, which will result in considerable loss of sugar-bearing mass. Therefore, it seems expedient to develop an automated controller, which would provide a solution to the problem of selecting shear height, setting the height automatically in the process of operating the haulm gatherer. To engineer the said controller, it is first necessary to find out the type of statistical distribution that describes the height that beet root crowns protrude above the soil surface. This issue has been tackled for many years by a number of researchers (Adamchuk et al., 2013; Bulgakov et al., 2018; Bulgakov et al., 2019) and they have predominantly favoured the normal (Gaussian) distribution. But the dependability of their results has been questioned because of the impossibility of obtaining sufficiently large samples by sampling and manual measurement.

MATERIALS AND METHODS

For an acceptably dependable assessment of the distribution of the height of sugar beet crowns in a field (distribution of plants in a row, distribution of height of root crowns above the soil, and loss during the harvesting) authors developed a laboratory-field unit (Fig. 1). The unit has been used in this research with the aim of reducing the loss of sugar-bearing mass incurred in the process of topping sugar beet roots. It involved the development of the technology for automated correction of the topping height.

The results of the accomplished measurements were processed with the use of recognised statistical methods on a PC. The main point of the statistical processing consisted of finding out the type of distribution that the measured heights to which the root crowns protruded above the soil surface and its statistical characteristics m and σ. After that, a forecast of the loss of sugar-bearing mass and the amount of residual haulm on the roots in relation to the height of topping without detecting could be prepared using the established model (Bulgakov et al., 2013). The input parameters of the model were related to characteristics of the root, the plantation conditions during the harvesting operations, and process control. The main parameters of the root included d_1, h_i (Fig. 2). The other parameters were derivative and could be calculated with the use of the relations provided in the papers by Bulgakov et al. (2013; (2019). The main field parameters included: m and σ – respectively, the statistical expectation and the standard deviation of the root crowns protrude above the soil surface (in case its distribution followed the normal probability); Q – was yield of roots per unit area (hectare); and N – number of roots in one hectare. The process parameters included height of topping without sensing h_z. The output parameters in the model were the direct values of the work process: lost sugar-bearing mass B and amount of residual haulm on the roots G, or their representation in terms of percentage of the total mass of roots. For modelling the process of defoliating the root crown, the geometrical model devised in the paper (Bulgakov et al., 2013) was used. The essence of the model consisted of determining the volume and mass of the crown of a single root with the use of the geometrical relations set out in Figs. 2, 3, 4. If the distribution of the heights by which root crowns protruded was known, the lost mass and residual haulm in relation to the cutting height could be forecast (Bulgakov, 2018). In order to change from a single root to the whole sample of roots in accordance with the above-mentioned technique, integration was carried out over the whole range of root crown heights taking into account the probability of occurrence of each value of the root crown height. The algorithm for integrating the losses in sugar-bearing mass and the amounts of residual haulm on the roots in relation to their position with respect to the soil surface and the topping plane was implemented in the computer program composed with the MatLab software.

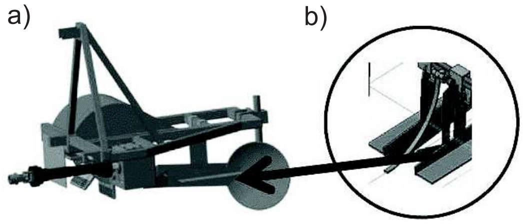

Figure 1. Laboratory unit (3D model) for measurement of height that sugar beet roots protrude above the soil level (a) and layout of its measuring unit (b).

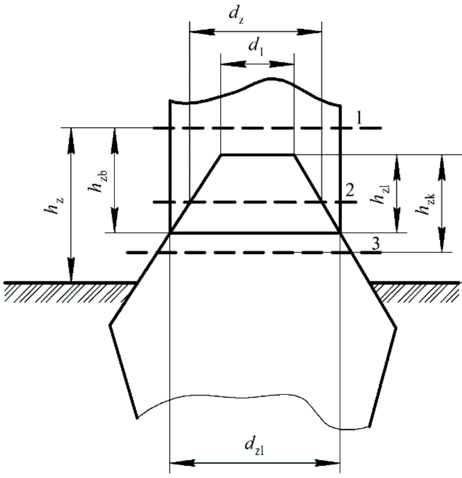

Figure 2. Geometrical model of sugar beet root crown that has bottom line of the haulm above soil surface level: h_i – root protrusion height (mm); h_{zl} – distance from top of root crown to bottom line of haulm (mm); h_z – height of topping without sensing (mm); h_{zk} – distance from top of root crown to topping plane (mm); h_{zb} – distance from topping plane to haulm bottom line (mm); G – haulm residual on roots (kg); B – loss of sugar-bearing mass (kg); ρ_b and ρ_b – densities of haulm and root (kg m^{-3}); d_1 – root crown top diameter (mm); d_z – root crown diameter in topping plane (mm); d_{zl} – root crown diameter in haulm bottom plane (mm):

Topping plane 1 is situated above the top of the root crown: In this case there is no loss of sugar-bearing material but haulm left on the root:

$$h_{zk} = 0, \tag{1}$$

$$h_{zb} = h_{zl} - h_{zk} + h_z, \tag{2}$$

$$B = 0, \tag{3}$$

$$G = \frac{\pi \cdot h_{zk} \cdot \rho_b \cdot d_{z1}^2}{4} - \frac{\pi \cdot \rho_b \cdot h_{ZL} \left(d_1^2 + d_1 \cdot d_{z1} + d_{z1}^2\right)}{12}. \tag{4}$$

Topping plane 2 is situated below the root crown top:

$$h_{zk} = h_i - h_z, \tag{5}$$

$$h_{zb} = h_{zl} - h_i + h_z, \tag{6}$$

$$B = \frac{\pi \cdot h_{zk} \cdot \rho_k \left(d_1^2 + d_1 \cdot d_{z1} + d_{z1}^2\right)}{12}, \tag{7}$$

$$G = \frac{\pi \cdot h_{zb} \cdot \rho_b \cdot d_{z1}^2}{4} - \frac{\pi \left(h_{zl} - h_{zk}\right)\left(d_1^2 + d_1 \cdot d_{z1} + d_{z1}^2\right)}{12}. \tag{8}$$

Topping plane 3 is situated below the haulm bottom plane:

$$h_{zk} = h_i - h_z, \tag{9}$$

$$h_{zb} = 0, \tag{10}$$

$$B = \frac{\pi \cdot h_{zk} \cdot \rho_k \left(d_{z1}^2 + d_z \cdot d_{z1} + d_z^2\right)}{12}, \tag{11}$$

$$G = 0. \tag{12}$$

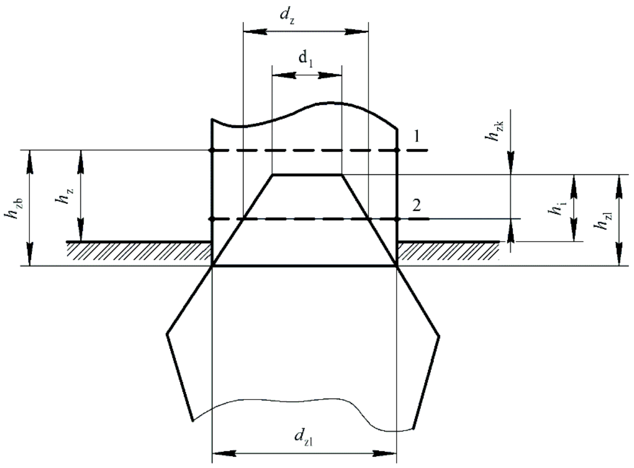

Figure 3. Geometrical model of sugar beet root crown that has bottom line of haulm below soil surface level:

Topping plane 1

$$h_{zk} = 0, \tag{13}$$

$$h_{zb} = h_{zl} - h_{zk} + h_z, \tag{14}$$

$$B = 0, \tag{15}$$

$$G = \frac{\pi \cdot h_{zb} \cdot \rho_b \cdot d_{zl}^2}{4} - \frac{\pi \cdot \rho_b \cdot h_{ZL}\left(d_1^2 + d_1 \cdot d_{zl} + d_{zl}^2\right)}{12} \tag{16}$$

Topping plane 2

$$h_{zk} = h_i - h_z, \tag{17}$$

$$h_{zb} = h_{zl} - h_i + h_z, \tag{18}$$

$$B = \frac{\pi \cdot h_{zk} \cdot \rho_k \left(d_1^2 + d_1 \cdot d_{z1} + d_{z1}^2\right)}{12} \tag{19}$$

$$G = \frac{\pi \cdot h_{zb} \cdot \rho_b \cdot d_{z1}^2}{4} - \frac{\pi\left(h_{ZL} - h_{zk}\right) \cdot \left(d_1^2 + d_1 \cdot d_{z1} + d_{z1}^2\right)}{12} \tag{20}$$

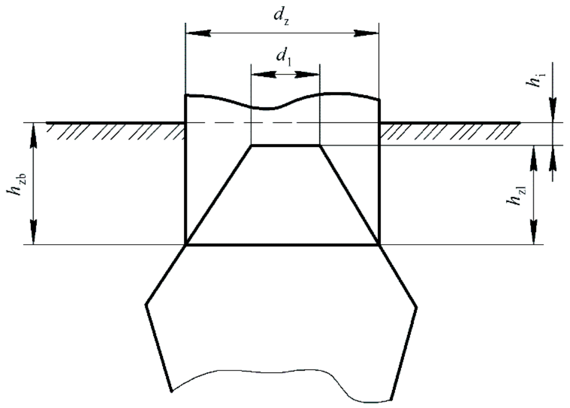

Figure 4. Geometrical model of sugar beet root crown that has top of root crown below soil surface level:

Topping plane 1

$$h_{zk} = 0, \tag{21}$$

$$h_{zb} = h_{zl} - h_{zk} + h_z, \tag{22}$$

$$B = 0, \tag{23}$$

$$G = \frac{\pi \cdot h_{zb} \cdot \rho_b \cdot d_{z1}^2}{4} - \frac{\pi \cdot \rho_b \cdot h_{ZL}\left(d_1^2 + d_1 \cdot d_{z1} + d_{z1}^2\right)}{12}. \tag{24}$$

As the first step, the authors developed the functional structure of such an experimental unit including data input and output modules, measuring unit (Fig. 5) control module, transducer module for logging the planting parameters (the positioning of sugar beet roots in the seeding row). An algorithm was also devised to control the process of measuring the height of the root crowns above the soil level.

The structural layout of the actual laboratory unit for the performance of field experiments includes a system of gyroscopes and accelerometers engineered to investigate the impact of the beet harvester's oscillations on the stability of performance of the sugar beet root harvesting implements.

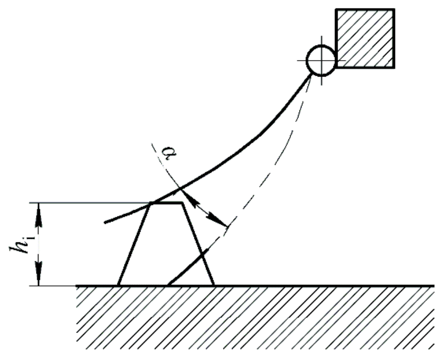

Figure 5. Schematic model of measuring root crown protrusion.

Figure 6. Experimental unit during field study of root crown protrusion above soil surface level.

The authors also developed the structural layout of the measuring unit and manufactured the electronic module to control the process of measuring the position of the sugar beet root crown above the level of soil surface. The measuring unit included sugar beet root detection feelers and other feelers that identify the position of the machine's wheelbase and the height that the crown of the sugar beet root protrudes above the soil surface. The height that the root crowns protrude above the soil surface was measured by the feeler (Fig. 5) that would deflect through an angle α, when it interacted with a root protruding to a height of hi. The deflection angle of the feeler was registered by the encoder comprising a magnetic disc and two A3144 Hall-effect sensors. At the moment when the magnet passed through the sensor zone, the sensors generated digital impulses, the number of which was proportional to the angle of deflection achieved by the feeler. The signal from the encoder was transmitted to the E-14-440 digital input-output board of the LCard brand. The E-14-440 module was connected through a USB connection to the PC with the LGraf program installed. In the process of measurement, the program generated a file with the data on the heights that the root crowns protruded above the soil surface. After collecting a sufficient number of measurements (over 50,000 roots), the file was exported into the Octave 4.0 problem-solving environment and there the loss in sugar-bearing mass and the amount of residual haulm on the roots were determined. The field studies were carried out with a single-row unit attached to a propulsion and power module (Fig. 6). The research was conducted in different beet fields with different biological yields of sugar beet roots and haulm, different geometry of the field surface, and a range of mechanical and physical properties of the soil. At the same time, graphs were plotted based on the results of processing a large sample (50 thousand measurements) on a PC with the use of dedicated MatLab software.

RESULTS AND DISCUSSION

The results of the research into the distribution of height of beet root crowns protruding above the soil surface are presented in Fig. 7. These graphs display a high degree of dependability and show the distribution of the heights that sugar beet root crowns protrude above the soil surface, depending on the intervals h indicated on the x-axis. Using a mathematical model (Adamchuk et al., 2013), the relationship between the loss of sugar-bearing mass and the height of topping sugar beet root crowns without sensing was obtained. Fig. 8 represents an example of the relationship (for one specific case) under the following distribution parameters: $m = 40$ mm and $a = 20$ mm. Nevertheless, in the same field these parameters were shown to vary within the limits indicated in Fig. 7. Therefore, the statistical parameters of the distribution should be monitored by a dynamic process. With their variation the graph of sugar-bearing mass (Fig. 8) as well as the optimal value h_z change correspondingly.

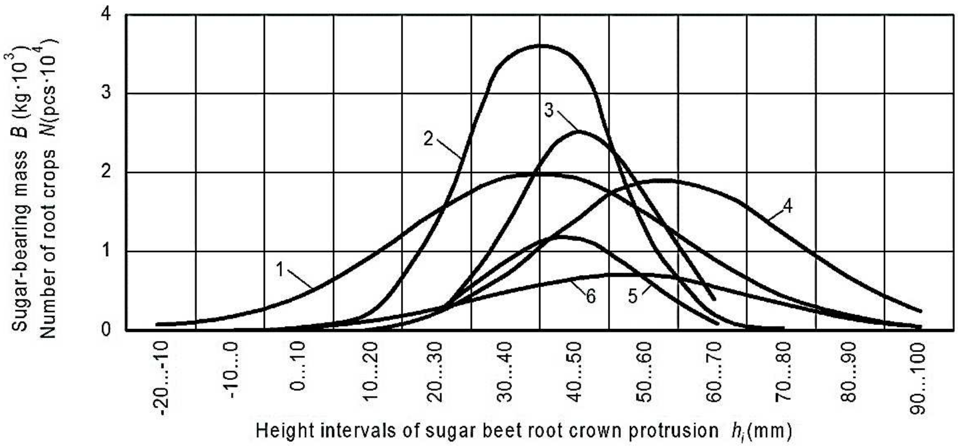

Figure 7. Distribution of heights of sugar beet root crown protrusion above soil surface where $m = 40$ mm: N – number of roots: 1) $\sigma = 10$ mm; 2) $\sigma = 20$ mm; B_z – sugar-bearing mass above ground: 3) $\sigma = 10$ mm; 4) $\sigma = 20$ mm; B_{3n} – sugar-bearing mass above ground containing haulm: 5) $\sigma = 10$ mm; 6) $\sigma = 20$ mm.

Fig. 8 can forecast the loss of sugar beet root mass and the rate of contamination of roots with haulm under specific conditions, once the statistical distribution parameters (*m*, *a)* have been established using the mathematical model presented by Adamchuk et al. (2013). That, in its turn, will allow an automated system of evaluating the parameters of sugar beet roots and promptly adjusting the height of shearing the haulm off the sugar beet rootsto be developed with the aim of reducing the loss of sugar-bearing mass.

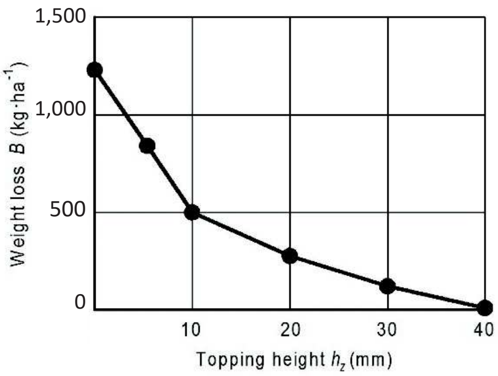

Figure 8. Relationship between loss in sugar-bearing mass (kg) and height of topping root crowns (mm).

Lines 1–2 in Fig. 7 show the distribution of the protrusion heights on the intervals, lines 3–4 the distribution of sugar-bearing mass on the protrusion height intervals, lines 5–6 the distribution of the sugar-bearing mass that needs cleaning from haulm.

CONCLUSIONS

1. The results of this research into the distribution of the heights that sugar beet root crowns protrude above the soil surface confirm the hypothesis that it follows the normal distribution.

2. The laboratory unit that was developed and the experimental study carried out with it provides the basis for the design of a system to automatically control the height of shearing haulm from the top of the roots in state-of-the-art root crop harvesters.

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