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A new way to unload combine harvesters at the field edge

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Abstract. A method of filling the combine hopper when it approaches the field edge and providing a to-and-fro method of a combine's movement in stints is justified. Formulas are given for calculating the operating width of the header and the working speed of movement, depending on the yield, length of the furrow and hopper capacity. The results of a comparative assessment of the traditional and the new methods of harvesting winter wheat with unloading of grain from the combine hopper at the edge of the field are presented.

1 Introduction

In recent decades, because of competition between companies for productivity, the dimensional characteristics of combine harvesters have increased significantly. Currently, the capacity of hoppers of certain CLAAS combine harvester models reaches 13.5 m^3, and that of New Holland - 14.5 m^3 with their weight of 18.9 and 20.0 tons, respectively [1]. This has affected the corresponding increase in the carrying capacity of vehicles used to transport grain from combines.

As a result of the changes that have taken place, the currently widely used combine harvesting technology for grain crops using vehicles with small-section tires (and others), which drive along the field has significant disadvantages:

- unpredictability of the combine hopper's filling places, the distances and duration of vehicles' journeys through the field leads to instability of the cars' working cycles. The necessity to ensure uninterrupted operation of combines leads to planning and using an overestimated number of vehicles and leads to significant losses of their time waiting for the next unloading. At the same time, despite an optimum combination of harvesters and cars, vehicle waiting times reach 30-36% [2], and with the use of high-performance road trains (KamAZ with a trailer for receiving grain from 2 or more combines) they reach 47%;

- increased wear of tires and transmissions of vehicles when driving in uncharacteristic conditions of the field with deformable soil and abrasive medium in the form of remaining stalks of standing crops;

- excessive compaction of the soil by chassis of the combines and small-section tires of vehicles when they drive across the field to the uploading points of the combine hopper.

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The initial requirements for basic machine technological operations in crop production (2005) limit the specific pressures of the movers of combine harvesters on the soil to 150 kPa with soil moisture less than 0.6 HB and 80-100 kPa - with moisture more than 0.6 HB [3]. But the maximum specific pressure of the wheels of Don-1500B combine with a filled hopper can reach 185 kPa and exceed the permissible value by 20% with soil moisture up to 0.6 HB and 1.8-2.3 times with soil moisture of 0.6-0.9 HB [4].

The problem of soil compaction with car wheels when harvesting crops is much more acute than its compaction with combines. The small-section tires of vehicles with increased carrying capacity (MAZ, KamAZ, etc.) with internal tire pressures of about 0.60-0.84 MPa and a single wheel load of up to 3-4 tons cause catastrophic pressures and stresses for the soil that exceed 6-8 times the maximum allowable ones [4].

With high yields achieved in the southern steppe regions, grain is loaded and unloaded from the hopper at almost every passage of the combine across the field, and with yields of more than 80-100 c/ha- two unloadings are possible, i.e. the number of field drives of vehicles is comparable with the number of passages of combines.

In connection with the excess of permissible pressure on the soil, there are problems associated with the decrease in effective fertility, with water permeability of soils, and an increase in their processing resistance [5]. It is believed that soil compaction during harvesting of cereal crops is the main obstacle to the transition to minimal tillage [6].

Especially significant compaction is possible when there is a lot of rainfall during harvesting and combine harvesters with vehicles severely deform moist soil. Thus, lumpiness is significantly increased during subsequent deep processing, especially during drying of arable layer in the previous period [7].

Scientists and practitioners have known about harmful consequences for the environment and soil productivity when using vehicles to carry grain from combines since reequipment of agricultural enterprises with heavy vehicles. With the permanent absence of an effective solution to the problem, the leading scientists of the Kuban and Voronezh State Agrarian University proposed to prohibit heavy trucks from entering the fields [8, 9].

However, the proposed use of expensive hoppers-reloaders in terms of solving the problem of soil compaction has not been confirmed and requires additional analysis. Since their capacity should not be less than twice the capacity of the hoppers, their aggregation requires tractors of the appropriate mass and power, which is also associated with the corresponding pressure of the multi-wheeled unit on the soil.

The most promising and radical proposal that is currently able to solve the problem of soil compaction by heavy vehicles when harvesting cereal crops is to unload grain from the combine hopper at the edge of the field [10, 11].

Currently, there is no industrially mastered method of harvesting grain crops with unloading the grain at the edge of the field without driving onto the field of vehicles (both cars and hoppers-reloaders), ensuring filling the entire volume of the combine bunker when it approaches the field edge and when it works without production loss. However, a solution to this problem can be found on basis of improving the working process of combine harvesters. Therefore, the above-mentioned growth trends in the parameters of harvesting and transport complex machines and the above disadvantages required searching for new technological solutions.

The purpose of the study is to substantiate a way to increase the efficiency of harvesting and transport complex when harvesting cereal crops by direct combining when unloading grain into motor vehicles at the field edge.

2 Materials and methods

The method of analysis of the published research results of the combine harvester's working process in the working cycles of filling the hoppers with grain, passing along the length of the furrow and working processes of vehicles when transporting grain from combines was used.

The method of mathematical modeling of a combine harvester's working process with a mathematical expression of factors, whose combination of the values ensures filling the hopper when approaching the field edge, with an expression of yield, length of furrow, hopper capacity as a function of the header's operating width is used.

The methodology of comparative field experience using the new method of harvesting cereal crops by direct combining [12] with timing observations of operation of the combine and the vehicle was used.

The distinctive feature of the proposed new method of combining with unloading a full hopper at the field edge is a new set of sequential actions containing:

- determination of grain yield on the field and the working speed of the used combine harvester (in the conditions of this field according to the level of permissible grain losses) when using the entire width of its header;
- calculation of the working width of the header of the used combine to ensure filling of the combine's hopper when it passes a distance that is a multiple of the furrow length, i.e. when approaching the field edge with a corresponding increased working speed, ensuring preservation of the actual feed to the thresher and performance of the combine (by grain output) per unit of main time;
- unloading grain at the field edge into the body of a vehicle performing transportation of the grain without driving across the field;
- using a to-and-fro method for a harvester to go through a working alley.

3 Results and discussions

Typical grain harvesting conditions in the Krasnodar Krai and in many farms of the southern steppe regions are the presence of rectangular fields with a developed network of field roads and high productivity.

The factors affecting pressure increase on the soil of high-performance technical means are both increased volumes of grain transported across the field in the technological capacities of harvesting and transport machines, and the increased mass of the machines themselves.

To the greatest extent, the re-equipment of harvesting and transportation complexes with high-performance combines and heavy trucks affects the southern steppe regions of the country due to high yields and large field sizes. Therefore, assessment of the negative consequences of technical re-equipment of harvesting is especially relevant in relation to these zonal conditions.

In the traditional technology of harvesting operations, the unpredictability of filling places of the combine hopper and distances and durations of vehicles' journeys through the field leads to the disruption of the rhythm when transporting grain to the thrashing floor and necessitates planning and usage of an overestimated number of cars, which is accompanied by an increase in waiting time in anticipation of the next unloading of grain. This limits productivity of vehicles and their performance indicators.

These shortcomings cause an obvious increase in the contradiction between the increase of grain transportation volumes from the fields (with an increase in yield) and a decrease in the efficiency of automobile operation, since the more powerful the car, the greater the cost of waiting time and traffic limitation with its use.

Unloading grain from a combine hopper at the field edge is one of the promising areas for improving production set-up and a progressive solution to the problems of the generally accepted pattern, which is possible on fields with the correct geometric shape and is especially relevant when moistening the soil during harvesting [10, 11]. The results are the following:

- elimination of the largest (in magnitude and penetration depth) soil compaction during harvesting by the running bodies of vehicles (cars or hoppers-reloaders) with a subsequent reduction in the cost of deep tillage (mainly for plowing);
- stable rhythm of automobile working cycles due to reception of grain from the combine at the field edge without driving along the field to the places of hopper loading in the basic method, which makes it possible to more accurately determine the need for cars depending on the remoteness of the field from the thrashing floor.

However, due to the probabilistic nature of filling the combine hopper when approaching the field edge (from 0.5 to 1.0 volume depending on yield, furrow length, hopper capacity and header width), when grain is unloaded from the hopper at the field edge, the loss of time for unloading is increased during the shift and the harvester's performance is reduced.

An analysis of attempts to improve the harvesting and transport process, with the use of hoppers-reloaders, shows that it is necessary to resolve this contradiction at a new organizational and technological level. In this case, exclusion of driving through the fields is relevant for preserving fertility and technological properties of soils, for limiting lumpiness and resistance to processing and maintaining water permeability.

It is relevant to search and ensure the design and operational parameters of combines that ensure maximum filling of hoppers at the edge of the field.

3.1 Theoretical justification of the proposed method of harvesting with unloading a filled hopper at the edge of the field

For small furrow lengths (up to 300-350 m), especially for small yields, filling the combine hopper requires multiple working alleys in the field, so visually or using calculation with the help of elementary formulas it is possible to determine the permissible number of alleys with unloading on one side of the field. Moreover, in comparison with the traditional method of harvesting, a decrease in the harvester's output due to a certain increase in the number of stops for unloading grain (owing to an insufficiently filled hopper) will be insignificant.

In fields with long length of furrows and large yields, a combine hopper can be filled after two or three working alleys in the field, and even before the end of the first alley. Moreover, when unloading grain at the edge of the field, the hopper can be half-filled or filled to its full volume.

As a result of operation analysis of harvesting and transport equipment for harvesting cereal crops and, in particular, winter wheat, it was found that in recent years in the southern steppe regions of the country, thanks to the achievements of selection, new technologies and the growth in the volume of used nutrients, grain yields increased significantly. This change outperforms re-equipment of most farms with new combines with a corresponding higher output of threshing and separating devices. Therefore, the optimum loading of threshers of most combines operating on farms occurs at relatively low operating speeds. Only in fields with low productivity, for loading the thresher, it is necessary to increase the working speed to acceptable values (according to the conditions of field uniformity). Based on this, in many cases, according to the conditions of field uniformity, the combine harvester has the potential to use an increased working speed. This circumstance opens up the possibility of combining the high-performance work of the combine with filling the hopper when it approaches the edge of the field and unloading grain from the hopper into the car at the edge of the field due to the choice of a combination of the working width of the header (with its partial movement along the mowed standing crops) and working speed.

Based on this, in many cases, according to the conditions of field uniformity, the combine harvester has the potential to use an increased working speed. This circumstance opens up the possibility of combining the high-performance work of the combine with filling the hopper when it approaches the edge of the field and unloading grain from the hopper into the car at the edge of the field due to the choice of a combination of the working width of the header (with its partial movement along the mowed standing crops) and working speed in accordance with the new method of harvesting cereal crops by direct combining with unloading of grain at the edge of the field [12].

With the full operating width of the header with the basic (traditional) work pattern, filling out of the hopper's volume Q, m^3 is directly proportional to the grain yield in the field, the width of the header and the alley length of the combine, and inversely proportional to the bulk volume of grain and is determined by the formula:

$$Q=\frac{У\cdot B_{p.o.}\cdot L_{nx}}{\gamma} \quad (1)$$

where $У$ is grain yield on the field, kg/m^2;

$B_{p.o.}$ is operating width of the header, m;

L_{nx} is length of the combine's alley for filling out the hopper, m;

γ is bulk mass of the grain, kg/m^3.

From (1) we find the expression for the length of the combine's alley L_{nx} across the field until the hopper is filled with grain:

$$L_{nx}=\frac{Q\cdot\gamma}{У\cdot B_{p.o.}} \quad (2)$$

The number of alleys across the field n until the hopper is filled up can be found by dividing the length of the combine's alley L_{nx} by the furrow length:

$$n=\frac{L_{nx}}{L_{г}} \quad (3)$$

where $L_{г}$ is the furrow length, m.

In the vast majority of cases, depending on the combination of yield, length of furrow, header width and hopper capacity, this value is not a whole number, which makes it necessary to drive across the field to receive grain from the filled combine hoppers to the place where the hopper was filled.

Filling out the entire volume of the hopper when a combine approaches the field edge is possible when passing a distance multiple of the furrow length of the field $(n\cdot L_{г})$, and for that the value n obtained from the division of L_{nx} by the furrow length $L_{г}$ needs to be rounded to the nearest larger whole number (this action is expressed by the corresponding mathematical sign $[n]$).

When using a short working width of the header, it is possible to fill the hopper after a whole number of alleys $[n]$, i.e. filling out the hopper with grain volume Q:

$$Q=\frac{У\cdot B_{p.x.}\cdot L_{г}\cdot[n]}{\gamma} \quad (4)$$

where $B_{p.x.}$ is a short working width of the header, m.

From the equality of the right-hand sides of expressions (1) and (4), it is possible to determine the working width of the header $B_{p.x.}$, using which filling out of the entire volume of the combine hopper will occur when it approaches the field edge (towards the furrow end):

$$B_{p.x.}=\frac{B_{p.o.}\cdot L_{nx}}{[n]\cdot L_{г}} \quad (5)$$

As can be seen from expression (5), the short working width of combine's header $B_{p.x.}$depends on the size of the full operating width of header $B_{p.o.}$, length of alley L_{nx}, necessary to fill the hopper when using the full width of the header and from the distance corresponding to the nearest larger whole number of furrows, i.e. a multiple of the length of furrow $[n]{\cdot}L_{г}$.

Maintaining the actual feed of grain mass into the combine's threshing machine while reducing the working width of the header is possible due to a corresponding increase in working speed, which follows from the expression of the actual feed into the threshing and separating device through the working width of the header, working speed and yield.

The actual feed into threshing and separating device q (kg/s) in the basic version of operation is calculated by the following formula:

$$q=B_{p.o.}{\cdot}V_1{\cdot}У \quad (6)$$

where V_1 is working speed in the basic version of combine's operation, m/s.

The actual feed into the threshing and separating device in the operating version with a short working width of the header and increased working speed can be obtained by the following formula:

$$q=B_{p.x.}{\cdot}V_2{\cdot}У \quad (7)$$

where V_2 is working speed in the new version of combine's operation, m/s.

From the condition of equality of the actual supply in the basic and new versions, i.e. from the equality of the right parts of formulas (6) and (7) we find the expression for calculating the increased working speed:

$$V_2=\frac{B_{p.o.}{\cdot}V_1}{B_{p.x.}} \quad (8)$$

Thus, filling out of the entire volume of the combine hopper when it approaches the field edge (the furrow end) is possible using a short width of the header, determined by formula (5), and preserving the actual feed rate to the combine's threshing and separating device (and, accordingly, the combine productivity per unit of time of main operation) due to an increase in its operating speed, determined by formula (8).

3.2 Comparative assessment of the new harvesting method

The comparative assessment experiment evaluating the operation of a combine harvester with a short width of the header using to-and-fro method in the new harvesting technology was carried out on July 25-26, 2019 in accordance with the methodology.

The field studies were conducted during harvesting of winter wheat 'Tanya' on the field of the KubNIITiM validation range. As a basic option, we have used an individual scheme of a combine harvester's operation with the following parameters - four alleys vertically and three alleys horizontally – Figure 1.

Fig. 1. Vertical operation of the combine harvester with a full width of the header.

Conditions of the comparative experiment corresponded to the typical ones taking shape during harvesting of winter wheat in the central zone of the Krasnodar Krai.

For practical verification of the proposed technological method in comparison with the basic harvesting method, *Desna-Polesie GS-12* combine harvester with a header width of 7 m and a *ZIL 4331* truck with a loading capacity of 6 tons were used.

To ensure visualization of the header's position relative to the edge of standing crops during the combine's operation under the new technological process, the central beam of the header reel was painted by stripes of three colors, clearly contrasting with the main color scheme of the header and standing crops – Figure 2.

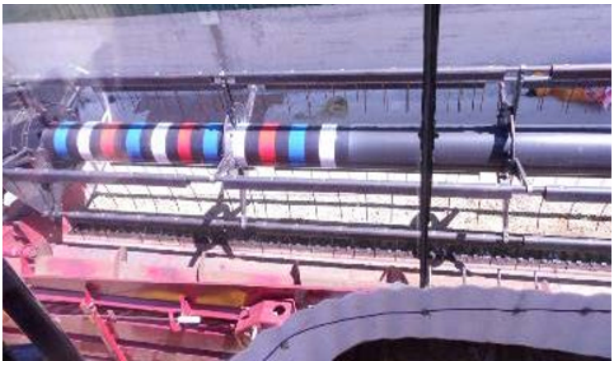

Fig. 2. View of the left block of color stripes from the workplace.

The width of the alternating unpainted stripes and color stripes was 10 cm, which was enough for satisfactory driving of the combine with the calculated parameters of the operating width of the header. The total width of the painted area on each side was 2.2 m. During calculations, it was considered that the total width of the header on each side was 0.2 m bigger than the width of the reel due to the movement of plants by dividers towards the cutting apparatus and the reel. Constant presence in the machine operator's field of view of bright colored stripes did not lead to discomfort in his visual perception of the workspace.

Established for reasons of completeness of grain harvesting and permissible grain losses, the combine's speed was 3 km/h. The harvest from a preliminary swath of 839 m long with a full operating width of the header amounted to 4720 kg, which corresponded to a yield of 81.3 c/ha.

As a result of calculations according to the formulas for filling the hopper in a double operating alley (to-and-fro), the working width of the header amounted to 4.6 m and the speed amounted to 4.6 km/h – Figure 3.

Fig. 3. Harvesting with a short operating width of the header.

The difference between average masses of grain in the hopper during unloading according to the basic operating version of the combine (when unloading the full hopper) and when working with a short operating width of the header and unloading at the edge of the field, obtained by weighing, is 215 kg. That is, in the new version, a place was initially left in the hopper for the unexpected supply of grain. However, during weighing of the grain according to the results of 8 cycles, stable indicators of grain mass were established: variation coefficient of 1.1 and 1.2%, respectively, when working in the new operating version and the basic operating version.

4 Conclusions

In relation to typical conditions for harvesting cereal crops in the southern steppe regions, a method for filling out the combine hopper by the time it approaches the field edge is substantiated, the essence of which is to apply a new set of interconnected operation modes of combine harvesters (working width of the harvester and working speed), determined depending on field conditions (yield, furrow length), while maintaining the optimum load of the thresher, as well as to apply the to-and-fro method of operation (without idle crossings within the stints) in all combinations of field conditions and operating modes with elimination of vehicles' drives through the field.

The formulas are given for calculating the working width of the header and the working speed, allowing to choose an operating mode of the combine on the field depending on the yield, furrow length and capacity of the combine hopper and to provide filling and unloading of grain at the field edge without reducing the combine's productivity.

In the conditions of increasing parameters of harvesting and transport complex machines, the new method of harvesting with unloading grain from the combine hopper at the field edge is one of the promising directions for improving production set-up, as well as a progressive solution to the problems of the generally accepted harvesting scheme, whose advantages are the following:

- elimination of the largest (in magnitude and penetration depth) soil compaction during harvesting by the running bodies of vehicles (cars or hoppers-reloaders) with a subsequent reduction in the cost of deep tillage (mainly for plowing);
- stable rhythm of automobile working cycles due to reception of grain from the combine at the field edge without driving along the field to the places of hopper loading in the basic method, which makes it possible to more accurately determine the need for cars depending on the remoteness of the field from the thrashing floor.

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