PAN POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2021.138162
2021, No. 50 (VI–IX): 69–73

The influence of scheme and tillage tool parameters on the material consumption and performance of chain tooth harrow

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RECEIVED 22.11.2020 REVIEWED 29.11.2020 ACCEPTED 21.06.2021

Abstract: The accumulation of moisture from autumn and winter precipitation in poorly draining soil for plants in arid conditions during the initial stage of the vegetation period in the northern region of Kazakhstan was a severe production problem. Research methods included theoretical and experimental studies. In theoretical studies, the area of the treated surface by a chain harrow is determined. Then, the design of an improved harrow is proposed, including how the tooth chain tillage tools are positioned. Either as a "single action disc harrow" type with mounting four teeth on each chain link, or as a serial harrow with the tooth chain tillage tools located in a "diamond-shaped" double-action scheme with two teeth on each chain link. Experimental studies show that an improved harrow steadily performs the early spring harrowing process with a quality that meets normative requirements. In doing, so the working capacity is 4–5% higher than a serial harrow with a 4–5% lower fuel consumption. Furthermore, it is revealed that the early spring soil harrowing performed by tooth chain harrows allows the loss of productive moisture in the spring pre-sowing period by 1.8–1.9 times to be reduced compared to the untreated background.

Keywords: arid conditions, chain tillage, chain tooth harrow, experimental studies, serial harrow, soil moisture

INTRODUCTION

The main limiting factor in increasing yields in the northern region of Kazakhstan is moisture. Due to the absence of moisture at the initial stage of their development, shoots are generally uneven. Winter precipitation is the primary source of moisture in this period. In Northern Kazakhstan, the following winter precipitation moisture accumulation techniques are used: leaving high standing stubble, seeding coulisses on pure fallow fields, herbicide (chemical) fallow field, snow riding, continuous combination crop harvesting; and forming coulisses of stubble. The instability of rainfall has added to the aridness of the climate. The average annual precipitation in the region is about 320 mm, (varying between 100 and 560 mm). The average rainfall during the vegetation period is 120 mm. Every three out of ten years, there is a severe drought. In the region, conditions are as follows; maximum summer precipitation (up to 60 mm) falls only in July, and in May–June, only 25–35 mm of precipitation falls. Sowing is carried out in May. The initial months of vegetation are accompanied by dry solid winds that dry up the soil. Analysis of climatic conditions shows that the primary source of moisture in the soil in the first half of the vegetation period of crop plants is the moisture of autumn and winter precipitation [VALIPOUR 2017]. In winter, there is about 90 mm of precipitation in the form of snow, quickly melting of which occurs in the first half of April. Studies showed that due to climate change in recent years in the northern regions of Kazakhstan, the amount of precipitation of the cold period increased by between 4–20%, the warm period decreased by 2–12% [ASKAROVA *et al.* 2018; BAISHOLANOV, POLEVOY 2017; DARBAYEVA *et al.* 2020; KURACH, AMANTAYEV 2020;]. This change indicates deterioration of moisture supply during the vegetation period of plants in the current.

Ordinary and southern chernozems represent the region's soils with humus content below 4% and dark chestnut soils with humus content below 3%. As a rule, these are poorly structural soils of heavy mechanical composition. Such soils with low humus do not accumulate a sufficient amount of moisture and poorly retain it. However, during drying, they are significantly self-consolidated, increasing hardness above 7 MPa.

After snow melting until sowing in the region conditions 3–4 weeks pass, during this period the soil intensively loses moisture by evaporation [EREMIN 2018; KULYASOVA 2018; PLOTNIKOV *et al.* 2018]. The adopted farming system includes chopping and spreading plant residues on the soil surface during harvesting crops and stubble leaving to eliminate soil erosion. However, these plant residues, at the crop yields up to 1500 kg·ha^{-1}, cannot fully protect the soil from drying [FUNAKAWA *et al.* 2007; KURACH, AMANTAYEV 2020; VOZHEHOVA *et al.* 2019; WALL *et al.* 2007]. Therefore, preserving the accumulated autumn and winter moisture during the period from snow melting to sowing is a serious production problem.

The effectiveness of mulching the topsoil to preserve soil moisture at the sowing depth was shown in studies. It was revealed that in the absence of mulching treatment for a period of 20–30 days from snow melting to sowing, moisture loss within the first metre of soil was about 30%. Moreover, the drying takes place mainly in the arable soil layer of 0–30 cm. During the early spring harrowing, moisture loss over the same period was about 10%. Scientific research and production experience indicate that the best way to meet work quality requirements, providing high productivity at low energy costs, is achieved with unpowered rotary tooth harrows. Such harrows are widespread in the fields of the northern region of Kazakhstan. The development of rotary tooth chain harrows was carried out in many studies [BAHRANI *et al.* 2007; CLARK 2002; KURACH, AMANTAYEV 2020; MASLOV *et al.* 2015; PHILLIPS 1998; PRASOLOV *et al.* 2016; SAUDER 2003]. A significant drawback of the development and use of rotary chain harrows is the scale of the construction scheme and the large consumption of materials.

This research aims to simplify the scheme and reduce the material consumption of the unpowered rotary tooth harrow.

MATERIALS AND METHODS

As a comparable analogy, we selected a serial produced chain harrow of Dvurechensky. The design of the tillage tools of a serial rotary tooth harrow is made in the form of a chain covering consisted of consistently connected links with two fixed teeth, which is shown in Figure 1.

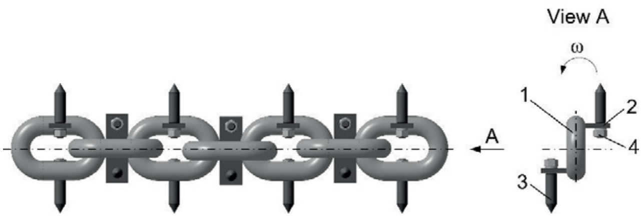

Fig. 1. Chain covering with tooth tillage tools of the serial harrow; view A – side view of the chain covering (sectional view); *1* = chain link, *2* = eye, *3* = tooth, *4* = screw, *w* = the direction of rotation of the chain tooth tillage tool; source: DVURECHENSKI and PRYTKOV [2013]

The technological process of this chain covering occurs as follows. Moving with rotation, the teeth of the tillage tools loosen the surface soil layer, break the large clods, uproot the small sprouted weeds, cover the weed seeds and plants with the soil, level the soil surface, and mulch its upper layer. Leaving the mass of stubble of the previous crop and other crop residues on the field's surface. The harrows used are made in a "diamond-shaped" scheme. Tillage is carried out in two ways. We have put forward the hypothesis that it is possible to provide the required quality of the technological process due to the combined action of two factors:
- simplification of the scheme of the chain harrow in one way;
- reducing material consumption due to the mounting of four teeth on each link instead of two.

In Figure 2, schemes of the known and proposed harrows are presented.

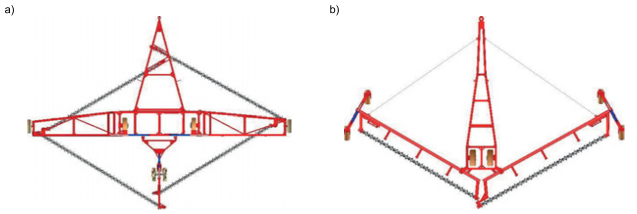

Fig. 2. Harrow schemes: a) scheme of the serial "diamond-shaped" harrow BZTs-12, b) scheme of the improved harrow of the "single action disc harrow" type; source: DVURECHENSKI and PRYTKOV [2013] and own elaboration

In Figure 3, the tillage tool of the improved harrow, the X-shaped teeth fixed through threaded joints in the holes in two curved plates welded on the outer sides of the link, is shown.

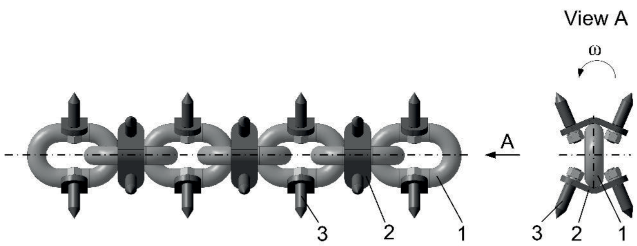

Fig. 3. Chain tooth tillage tool of the improved harrow; view A – side view (sectional view); *1* = chain link; *2* = plate; *3* = cone-shape ended tooth; *w* = direction of rotation; source: own elaboration

RESULTS AND DISCUSSION

As mentioned earlier, the study the influence of the agricultural practice "early spring harrowing" performed by the compared chain harrows on the productive soil moisture reserves before sowing. Research methods included theoretical and experimental studies. In theoretical studies, the area treated by each tooth was determined, then by summing up the area of the treated surface by the chain harrow in the test area. During theoretical calculations of the treated surface, the graph analytical method of research was used, described in detail in our publication [KURACH *et al.* 2019]. The area of the treated surface was calculated using the program COMPAS-3D.

During experimental studies, the agrotechnical and operational-technological indices were evaluated according to the requirements of Standards [GOST 33687 2016; GOST R 52778 2007; FEDORENKO *et al.* 2019; KURACH, AMANTAYEV 2020]. Table 1 shows the field conditions determined according to GOST 20915 [KONSTANTINOV *et al.* 2016]. They can be described as typical for the zone.

Table 1. Field conditions of experimental studies of the compared harrows

Index	Value/Description
Soil type	chernozem with the texture of medium loam
Surface relief, microrelief	smooth, levelled
Soil moisture (%) in the layer (cm):	
0–5	27.7
5–10	31.2
10–15	29.9
Soil hardness (MPa) in the layer (cm):	
0–5	0.38
5–10	0.65
10–15	0.83
The amount of crop residues (g·m^{-2})	219.4
The roughness of the surface (cm)	3.1

Source: own study.

Calculations show that an increase in the number of teeth from two to four with a decrease in the number of chains from two to one on the proposed harrow allows the surface area by 8% to be increased compared to the serial chain harrows of the diamond type (Tab. 2).

Table 2. The surface area of the compared harrows

Scheme of harrows and design of their tillage tools	The radius of the *t (mm)*	The spacing of the tillage tools (mm)	The specific area treated by the tillage tools (% from the test area)
Serial harrow	125	96	53.2
Improved harrow	125	96	57.6

Source: own study.

It was revealed that the transition to a new scheme of the chain harrow (in one way as a "single action disc harrow" type) could reduce its material consumption by 30%.

In Table 3, the agrotechnical indices of the improved chain harrow compared to the serial harrow on the early spring harrowing are shown.

From Table 3, it is seen that the performance indices of the technological process of early spring harrowing with an improved harrow correspond to the agrotechnical requirements and are on a par with the indices provided by the serial tooth chain harrow.

In Table 4, the results of the evaluation of the operational performance of the harrow units are shown. It is revealed that the working capacity for one hour of the main and shift time of the improved harrow at a speed of 14.7 km·h^{-1} was 17.64 and 14.64 ha·h^{-1}, respectively, which is exceeds the productivity of a serial harrow by 4–5%, with a 4–5% lower specific fuel consumption.

Table 3. Agrotechnical indices of the compared harrows

Index	Value of indices:		
	according to agrotechnical requirements	according to trails	
		serial harrow	improved harrow
Travel speed (km·h^{-1})	10.0–15.0	14.1	14.7
Tilling depth of the tillage tools (cm)	5.0±1	5.1	4.5
Clod size distribution – fractions up to 25 mm (%)	≥80.0	83.2	84.7
Breaking up the soil surface crust (%)	≥75.0	85.9	87.1
Residue retaining (%)	≥80.0	82.0	85.0
Roughness of the soil surface (cm)	≤3.0	2.5	2.2
Blocking of the tillage tools	not allowed	no	no

Source: own study.

Table 4. Operational indices of the harrow units

Index	Value acc. to:		
	agrotechnical requirements	trail	
		serial harrow	improved harrow
Travel speed (km·h^{-1})	10.0–15.0	14.1	14.7
Working width (m)	12.0	12.0	12.0
Working capacity for one hour of the main time (ha·h^{-1})	–	16.92	17.64
Working capacity for one hour of the shift time (ha·h^{-1})	–	14.04	14.64
Specific fuel consumption (kg·ha^{-1})	–	1.51	1.45

Source: own study.

In Table 5, the results of the assessment of the influence of the "early spring harrowing", an agricultural practice carried out by the compared chain harrows on the productive soil moisture reserves, are shown.

The results indicate that the implementation of the early spring harrowing with the tooth chain harrows can reduce the soil moisture loss in the pre-sowing period by 1.8–1.9 times compared to untreated soil. Moreover, the difference in soil moisture losses between serial and improved tillage tools is insignificant.

Table 5. The influence of the agricultural practice "early spring harrowing" performed by the compared chain harrows on the productive soil moisture reserves before sowing

Variant	Agricultural period	Productive soil moisture reserve in a layer of 1 m (mm)	Moisture loss (%)
Background before treatment (control)	24th April	228.0	–
Background before sowing without treatment	14th May	159.4	30.1
Before sowing after serial harrow	14th May	192.5	15.5
Before sowing after the improved harrow	14th May	189.1	17.0

Source: own study.

The previous studies emphasised that to retain moisture at a depth of the upcoming sowing (6–8 cm), early spring harrowing is used. This technological operation is performed to a depth of 4–5 cm and should provide:
- destruction of soil capillaries;
- breaking up of the dry soil crust on the field surface;
- filling of existing cracks in the soil;
- retaining of 70–90% of stubble and even distribution of plant residues chopped by the harvester across the field;
- creation of a dry mulching layer on the surface covering the moist lower soil layers.

The effectiveness of mulching the topsoil to preserve soil moisture at the depth of sowing was shown in studies by Barayev [1988], Moldenhauer and Black [1994], Artamonova *et al.* [2019], Astafyev *et al.* [2019], Chen *et al.* [2019], Gusev [2020], Toigildin *et al.* [2020]. It was revealed that in the absence of mulching treatment for a period of 20–30 days from snow melting to sowing, moisture loss in a meter layer of soil was about 30%. Moreover, the drying takes place mainly in the arable soil layer of 0–30 cm. During the early spring harrowing, moisture loss over the same period was about 10%.

As mentioned earlier, this paper tried to simplify the scheme and reduce the material consumption of the unpowered rotary tooth harrow. The current study results indicated that the improved chain tooth harrow could be recommended for use since, at the same performance indices, it can reduce material consumption by 30% compared to the serial chain tooth harrows.

CONCLUSIONS

1. An effective agrotechnical practice of preserving moisture in the pre-sowing period is the early spring harrowing. For its implementation, the most promising machines are the rotary harrows with the tooth chain tillage tools.

2. Serial harrows with the tooth chain tillage tools positioned in a "diamond-shaped" double-action scheme with two teeth on each chain link have high material consumption and large sizes.

3. The design of an improved harrow is proposed. The tooth chain tillage tools are positioned in one way as a "single action disc harrow" type mounting four teeth on each link, allowing the material consumption to be reduced by 30% compared to the serial harrow.

4. Experimental studies have shown that the improved harrow steadily performs the early spring harrowing process with a quality that meets normative requirements. In doing so, its working capacity is 4–5% higher than a serial harrow with a 4–5% lower fuel consumption.

5. It was revealed that the early spring soil harrowing performed by tooth chain harrows allows the loss of productive moisture in the spring pre-sowing period by 1.8–1.9 times to be reduced. Moreover, the difference in soil moisture losses between serial and improved harrows is insignificant.

FUNDING

Ministry of Education and Science of the Republic of Kazakhstan Grant No. AP05130663 and No. AP05133043.

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