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STRUCTURAL-AGGREGATE COMPOSITION AND SOIL WATER RESISTANCE BASED ON TILLAGE REGIMES IN SOUTHEAST KAZAKHSTAN

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SUMMARY

The promotion and rational development of drylands employed two tillage regimes (plowing to 20–22 cm and no-till) during the spring wheat and barley cultivation in Southeast Kazakhstan. The results established that the no-till scheme contributed to forming an excellent aggregate state of the arable soil layer for spring wheat and barley (65%–69%). The water-resistant aggregates were the highest with no-tillage (19.3%–21.8%), indicating the unsatisfactory water resistance of the soil structure. Enhancing the water-resistant aggregates requires using organic fertilizers to improve the establishment of perennial grasses, green manuring, and cover crops. No-till system inclined to boost the optimal soil density from a loose and slightly compact state of 1.19–1.23 g/cm^3 to a dense 1.32–1.39 g/cm^3. According to crop cultivar and tillage methods, the spring wheat and barley grain yield varied between 2.84 and 3.89 t/ha. High grain yield came from the spring barley cultivar Symbat. Spring showed promising performance when the plowing level was 20–22 cm and inferior only by 0.25 and 0.15 t/ha with no-till. Based on the two-factor analysis of variance, the cultivar contribution to the spring wheat and barley grain yield buildup depended on the shares of crop season of the research (year - environment) (40.9%–62.2%) and the tillage regimes (22.4%–32.2%). The grain yield formation was more dependent on the studied crops and their cultivars, and the dependence increased over the crop seasons due to weather conditions during the crop period.

Keywords: spring wheat, barley, soil, soil structure, tillage regimes, no-till, grain yield

Key findings: Structural-aggregate composition and water resistance of soil depended on tillage methods in Southeast Kazakhstan..

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INTRODUCTION

Current wide use of the resource and moisture-saving technologies of minimal and zero tillage persists (Korchagin *et al.,* 2014). Worldwide, no-till cultivation covers around 60 million ha of area and about 200 million ha with minimum tillage, and these numbers are gradually increasing. Mini-tillage and zero tillage significantly reinstated natural soil fertility (Galkin *et al*., 2016). Therefore, an enormous experience has built up in using mini- and no-till cultivation of various crops.

In this field, the first successful cultivation of grain crops occurred in Northern Kazakhstan (Karabaev *et al*., 2005). According to FAO data, in 2009, Kazakhstan entered the top 10 countries with the introduction of zero tillage to 1.5 million ha, and by 2014, the area had increased to two million ha (Karabayev *et al*., 2015; Gusev *et al*., 2022; Bastaubayeva *et al*., 2023; Kenenbaev *et al*., 2023). However, the introduction of no-till became a preference in non-irrigated lands of Northern Kazakhstan. In 2012, Kazakhstan ranked first in Europe and Central Asia and seventh in the world with zero tillage. Research on the development of mini- and no-till has recently progressed in the drylands of Southeast Kazakhstan. Under these conditions, improving the farming system based on resource-saving and soil-protecting technologies became the main focus (Kireev and Saparov, 2010).

In the 1990s, the acreage decreased sharply; however, to date, said soil area belonged to the arable category. Long-term land utilization with a low level of agricultural technology has led to a sharp decrease in soil fertility, including a significant decline in the soil's carbon accumulation, erosion, and deflation. In the last few decades, climate change has shown an association with an imbalanced distribution of precipitation and immense fluctuations in temperature due to enhanced CO_2 concentration in the atmosphere. Past studies conducted on the drylands of Southeast Kazakhstan revealed that using zero tillage with light mechanical composition on gray soils has a definite advantage over using mechanical tillage. Direct sowing was possible on light, chestnut soils, with heavier composition texture provided grain crop cultivation technology was intensified (Kireev, 2010).

For rational use of drylands in Southeast Kazakhstan, upgrading the existing cultivation technologies is crucial to introduce soil protection technologies. These technologies will improve soil organic matter and solve environmental issues, including the greenhouse effect; hence, their further expansion deserves special attention. The search for technologies that integrate these processes has led to the introduction of mini- and zero tillage, which recently have an increasing use globally. Mini- and no-till improve soil cover, reduce soil destruction, increase the soil content of organic matter, and positively affect regional farming systems. The basic principle of the technology the study is developing will have the basis of using soil-protective technologies for cultivating crops in the drylands of Southeast Kazakhstan. Over the previous centuries, agriculture strengthening has been declining in the soil carbon content by 30%–50% and plant genetic resources at large.

Arable soils could serve as the most vital carbon sink, and an increase in carbon reserves in the upper layer by only 0.4% per year can essentially compensate for anthropogenic greenhouse gas emissions into the atmosphere. The soil carbon dynamic models consider the achievement of several goals, i.e., crop rotation productivity management, adaptation to expected climate changes, increased intake of residues and organic fertilizers, reduction of unproductive losses, and economic analysis of advantages and obstacles in implementing agricultural technologies (Kontoboitseva *et al.,* 2020).

Worldwide, the arable soil layer depth contains about 680 billion tons of carbon, almost twice the same in the atmosphere. More than 60% of this carbon concentrates in just 10 countries (in descending order: Russia, Canada, the US, China, Brazil, Indonesia, Australia, Argentina, Kazakhstan, and Congo). Improving soil management enhances the soil organic carbon, which can help maintain yields in arid conditions. Therefore, it is earnestly required to take indispensable measures for further sequestration where situations allow.

With the help of the ARMOSA program (Valkama *et al*., 2020), researchers modeled the dynamics of soil organic carbon over 20 years under various farming systems (including organic farming) in Italy, Finland, and Kazakhstan based on the current climate. The traditional techniques remove carbon from the soil at all sites (600–800 kg ha^{-1} per year), but the innovative farming systems (crop rotations + no-till + cover crops) allow carbon storage in the soil (sequestration of CO_2). However, the maximum increase of organic carbon was evident at the site of Almaty, Kazakhstan (1.14% per year, equivalent to 1200 kg ha^{-1} per year). In Kazakhstan, soil-protective agriculture and its various measures have great potential for carbon sequestration, especially in irrigated lands, which allows the rotation of high-yielding crops with cover crops.

The organic substances' accumulation in the upper soil layer due to the constant covering of the soil with mulch is a key mechanism beneficial in soil conservation and moisture. The soil organic matter accumulation and carbon is limited in the upper 10 cm of soil layer (Gattinger *et al.,* 2011). The removal of plant residues leads to nitrogen deletion and reduction of the potential of carbon for binding organic carbon, leading to its loss (William and Kuzyakov, 2018).

Estimates of carbon sequestration using the no-till and mulching system demonstrate that the sequestration rate varies widely, from 50 to 150 kg ha^{-1} per year in arid zones to 1000–1500 kg ha^{-1} per year in humid climates (Lal, 2004, 2011). An increase in the carbon reserve in the upper soil layer of 0.4% is possible for agricultural lands due to correct agrotechnological solutions employed and optimization of the land use structure (Romanenkov, 2018). Thus, the presented research sought to study the influence of various tillage regimes on the agrophysical properties of light, chestnut soil in Southeast Kazakhstan.

MATERIALS AND METHODS

Plant material

Evaluation of the source material by the ability to use favorable environmental factors with superior efficiency and simultaneously resist environmental stressors was the primary condition for the allocation of new cultivars characterized by a reduction in costs per unit of yield (Katkov, 1999), as well as, the introduction of drought-resistant high-yielding crops that can grow throughout Kazakhstan. Such an introduction was the most effective solution to the issue of climate change and decreasing precipitation.

For assessing and implementing soil protection technologies, the field experiments ran in the drylands of Southeast Kazakhstan. In the semi-secured drylands of Southeast Kazakhstan, the research material was spring wheat (cultivar Kazakhstan 10 and a promising Canadian number) and spring barley (cultivar Symbat and an excellent Canadian number). Field experiments used two-tillage methods (plowing to a depth of 20–22 cm and no-till) with three-fold repetitions, and the placement of experimental plots was systematic. Sowing of spring crops began on the third day of March using a direct sowing drill, Vence Tudo-7500 (Brazil), with the simultaneous introduction of 100 kg of ammophos (P_{50}) into rows. The plot area was 440 m^2 (4.4 m width × 100 m length), with a seeding rate of 170 kg ha^{-1}.

Study location

The chief task of agricultural producers is to obtain high yields. However, the territory of Kazakhstan is characteristic of a wide variety of natural and climatic conditions. Around 80% of the cultivated area has insufficient moisture, including the drylands of Southeast Kazakhstan, characterized by increased aridity. In this region, the drylands amount to 1.4 million ha of the total area. In Southeast Kazakhstan, according to the annual precipitation, absolute altitude above sea level, and total radiation, the drylands comprised three categories, i.e., unsecured (with a yearly rainfall of 200 to 280 mm), semi-secured (280 to 400 mm), and secured (over 400 mm). The maximum share falls under unsecured drylands (64%), while semi-secured and secured drylands comprised 26% and 10%, respectively (Zhapayev *et al.*, 2023). Therefore, there is a need to study soil protection technologies for cultivating various crops, and one of the main factors is the tillage system.

In crop cultivation and production, tillage is one of the most energy-intensive processes. It is the most expensive and complex cultivation operation, organizationally slow, fuel-demanding, labor-intensive, and environmentally unfavorable (Stajnko *et al.*, 2009). The pertinent research on the development of zero-tillage in drylands proceeded in 2018–2020 on light, chestnut soil, with a humus content of 2% and medium availability of phosphorus and increased potassium, at the Stationary Laboratory of Agriculture, Kazakh Research Institute of Agriculture and Crop Production (KRIACP), Almaty Region, Kazakhstan. The research ran against the background of nitrogen-phosphorus fertilizers. The P_{50} application ensued during sowing, and N_{35} in the spring phase at the beginning of tillering.

The presented study conducted laboratory studies and soil analysis in the accredited Laboratory of Soil Science and Agrochemistry of the Kazakh Research Institute of Agriculture and Crop Production. The field experiments, observations, and compilation proceeded according to the Dospekhov method. The determination of structural-aggregate composition and water resistance of the soil used the Savvinov method.

Weather conditions

According to the Ministry of Environment and Water Resources, Republic of Kazakhstan, the climate will become warmer and wetter. The average scenario predicts an increase in the average annual temperature of 1.7 °C by 2030, 2.9 °C by 2050, and 4.1 °C by 2085. Precipitation will increase by 7% (2030), 8.1% (2050), and 9.9% (2085) compared with the base period of 1961–1990. The maximum increase in precipitation will occur during winter, i.e., by 14% (2030), 21% (2050), and 28% (2085). An expected short-term increase of 2.8% in precipitation will also surface during summer (UN FCCC, 2013).

The data from the Almalybak Meteorological Station of the KRIACP, Almaty Region, Kazakhstan, helped to characterize climatic conditions and describe their impact on the production of spring crops. According to the long-term data of the KRIACP Weather Station, the average annual air temperature was +7.6 °C, and the hottest month of the year was July, with an average monthly air temperature of 24.1 °C. The predicted temperature below 5 °C could occur on days 2 and 3 of October. Stable snow cover formation will appear in late November–early December and remain for 85–100 days. The sum of positive temperatures during the active plant vegetation phase (April-September) reaches 3515 °C. During the same period, the precipitation in the region also varies widely, from 219 to 291 mm. According to the long-term average data, the most downpour falls in the spring.

According to the Weather Station of the KRIACP, meteorological conditions for 2018–2020 were favorable, and the precipitation was 267.5–320.7 mm, 68.9–122.1 mm higher than average long-term (Table 1). The average air temperature for four months over the years was 18.5 °C–19.6 °C, which was 0.5°C–1.6 °C higher than the average long-term. The precipitation that fell during the months of April-May contributed to the sufficient accumulation of productive moisture reserves in the soil, allowing even sprouts and regular growth and development in the initial period of growth and development of spring wheat and barley. Thus, the climatic conditions during the research period (2018–2020) were favorable for the growth and development of plants and grain yield of spring wheat and barley. Statistical analysis comprised a two-factor analysis of variance (ANOVA) of the treatments for various

Table 1. Average monthly air temperature and precipitation during the vegetation period.

Month	Air temperature (°C)				Precipitation (mm)			
	2018	2019	2020	Long-term mean	2018	2019	2020	Long-term mean
April	12.4	12.4	14.2	10.4	81.6	183.0	146.7	56.5
May	16.4	16.9	18.7	16.4	124.9	39.3	73.5	61.6
June	22.3	22.3	16.5	21.2	28.7	72.7	42.6	53.9
July	25.2	26.9	24.4	24.1	32.3	25.7	38.1	26.6
For 4 months	19.1	19.6	18.5	18.0	267.5	320.7	300.9	198.6

parameters, and the treatments' differences were considerably significant at $P < 0.005$.

RESULTS AND DISCUSSION

Soil density in light chestnut soil

The soil density is an indicator of the agrophysical state of the soil, on which the growth and development of the crop plants depend, and it should be within certain limits, called the optimal range. For the majority of the crops in loamy soils, the optimal density range is 1.00–1.30 g/cm^3 (Kurachenko *et al.*, 2018). As the total humus content decreases, the optimal density shifts toward compaction. Physical conditions of soil affect both the mobilization processes and the effectiveness of the applied mineral fertilizers.

The influence of tillage regimes, including zero tillage, on soil density caused an active discussion among various scholars. In zero-tillage, the prolonged rejection of basic tillage contributes to the formation of plant mulch and serves as an analog of underlayer from plant litter (Polyakov, 2021). Researchers observed a sharp increase in soil compaction of the upper soil layer by 0.05–0.09 g/cm^3 during the first four years; in the fifth and sixth years, the difference in density compared with deep loosening sharply decreases to 0.01–0.03 g/cm^3 (Bakirov *et al.,* 2018). These results also gain support from past findings on the same type of research (Blanco-Canqui and Ruis*,* 2018; Li *et al.,* 2019).

Determination of the density of light chestnut soil under spring wheat and barley in the arable soil layer (0–30 cm) in three layers (0–10, 10–20, and 20–30 cm) showed significant variations, both in the layers and depending on the cultivated crops. According to Kazakov (1997), during the dry crop seasons, the optimal density values were higher, and for wheat were 1.00–1.20 g/cm^3, while in wet years, the rate was lower by 0.10 g/cm^3. According to Kovalev (1992), the range of optimal density parameters expands under sufficient moisture conditions.

The given experiments showed an increase in the optimal soil density level in the spring after sowing and before harvesting. In spring, the soil under the studied crops was loose and slightly compacted (1.19–1.23 g/cm^3). By harvesting, its density increased and became dense (1.32–1.39 g/cm^3), especially with no-till (Figure 1). According to Kuznetsova *et al.* (2011), cultivars with acceptable values of equilibrium density (1.30–1.40 g/cm^3) were most common in this range of soil density in chestnut soils of the dry steppe zone.

Structural condition of light chestnut soil

Soil structure is an influential property, mainly determining soil's physical and chemical characteristics and fertility. The optimal conditions of water, air, and thermal regimes develop in the structural soil, which, in turn, determines the development of microbiological activity, the mobilization of nutrients, and their availability to crop plants. Lumpy-granular structures with the size of aggregates from 0.25 to 10 mm, having porosity and water resistance, are agronomically more valuable. This structure determines the most favorable water-air soil regimes (Nebytov, 2005).

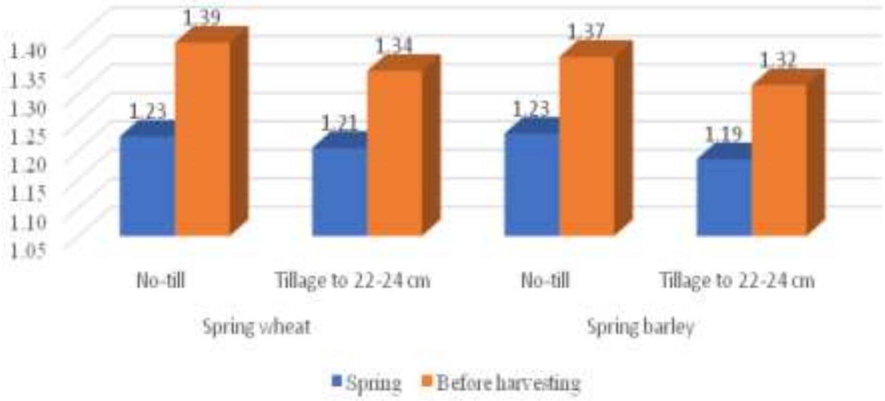

Figure 1. Soil density in light chestnut soil during the vegetation period (layer 0–30 cm, g/cm^3) and average for 2018–2020.

With combined deep, minimum, and zero processing systems, the structural aggregates' content (0.25–10 mm) increases in comparison with the control (dump deep) in barley crops, while the proportion of the lumpy (macro aggregates greater than 10 mm) fraction decreases. With direct sowing, agronomically valuable aggregates form in optimal quantities; with traditional cultivation technology, the proportion of the pulverized fraction increases, which, in turn, increases the susceptibility of the soil to erode and deflate. In direct sowing, a higher soil water resistance appeared (Volters *et al*., 2020; Gusev *et al*., 2022; Bastaubayeva *et al*., 2023; Kenenbaev *et al*., 2023). According to Baybekov's (2018) findings, negative consequences occur during dump processing. The soil's natural composition breaks, and the upper and lower layers change places. Thus, oppressing the soil fauna, with the structure and water resistance of aggregates also disrupted, and the number of macro aggregates increased. Plowed soil dries faster and undergoes erosion, with the organic matter content decreased.

Long-term research has established that the structural-aggregate composition of the arable soil layer significantly affects plant growth conditions, changing the agrophysical properties of the soil, including its structure (Vorontsov and Skorochkin, 2019). In these studies, the assessment of the structural-aggregate composition of the arable soil layer (0–30 cm) showed that the content of agronomically valuable aggregates (10–0.25 mm) gained more effects from tillage regimes than from culture (Figure 2).

The studied tillage regimes provided a superior (65%–69%) soil structural condition of agronomically valuable aggregates (0.25–10 mm) in the soil layer of 0–30 cm during the spring wheat and barley vegetation period, with dry sieving. However, the maximum content of structural aggregates (69%) was notable in spring barley sowing with no-till. It indicates an excellent soil aggregate state with these crops under natural conditions. The minimum structural aggregates (65%) were visible in spring wheat sowing when plowing reached 20–22 cm. The content of water-bearing aggregates was the highest in the variants with no-till, with indicators ranging from 19.3% to 21.8%, while with plowing to 22–24 cm, the water resistance of aggregates in crops declined to 20.8%.

Crop yield based on tillage regimes

The crop yield is the potential of the genotype in interacting with environmental factors, especially meteorological ones. In some crop seasons, the losses due to unfavorable conditions were 50%–65% (Kovtunova *et al*., 2022). In the presented study, the grain yield of spring wheat and barley depended on the crop cultivar and tillage methods, varied with ranges of 2.84–3.89 t/ha (Figure 3). The highest grain yield resulted in barley cultivar

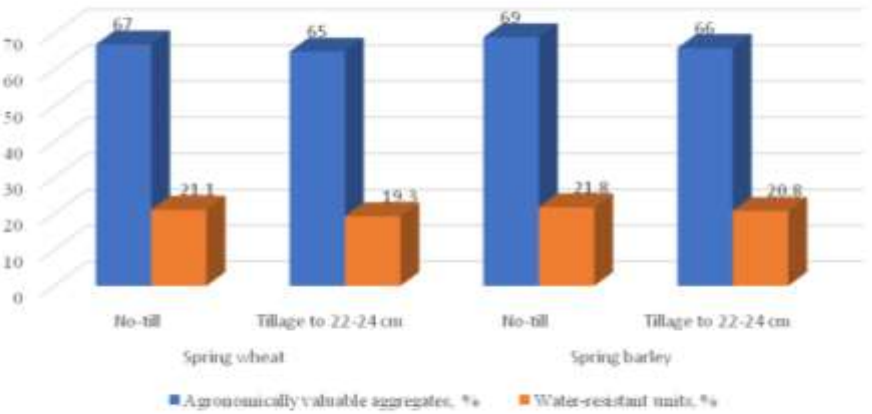

Figure 2. Structural condition of light chestnut soil with different tillage methods and average for 2018–2020.

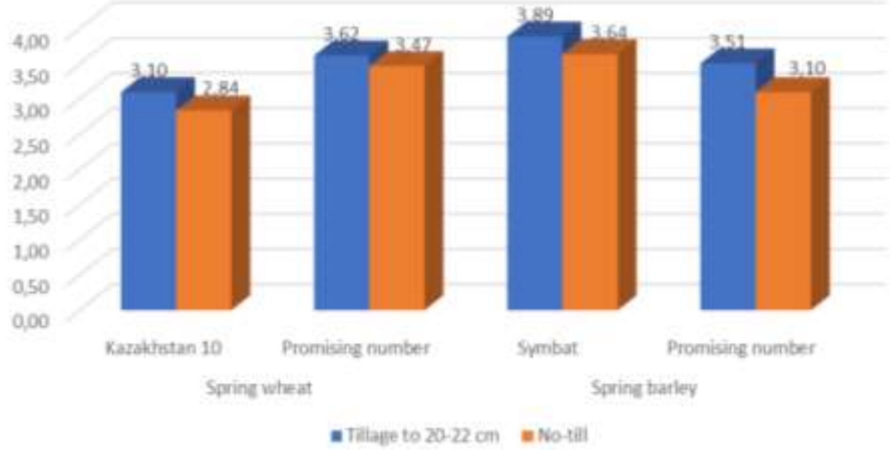

Figure 3. Grain yield of spring wheat and barley, depending on tillage methods, and average for 2018**–**2020.

Symbat with plowing to 20–22 cm, with no-till, and inferior only by 0.25 t/ha. For spring wheat, the highest grain yield came from the promising number with plowing to 20–22 cm and the no-till was inferior by only 0.15 t/ha. According to various researchers, no-till stabilizes yields over the years (Zhang *et al.,* 2015; Keil *et al.,* 2020*)* and requires at least 4–6 years to realize its potential (Govaerts *et al.,* 2005; He *et al.,* 2011).

According to other sources, grain yield with zero-tillage compared with plowing decreases significantly in the first years of study. By the year sixth and seventh, it shows a tendency for a gradual reduction of the difference, and by the ninth year, some advantages of zero-tillage were evident (Polyakov, 2021). The positive response with no-till correlated with the incoming organic matter amount, affecting the organic matter accumulation and the improvement in soil properties (Jat *et al.*, 2019). A slight increase in soil density mainly has the moisture conditions during the crop season determining it and not tillage regimes. Thus, the significant influence of weather conditions of the vegetation period and the hydrothermal coefficient was confirmatory, and the grain yield did not depend only on the tillage methods (Zhelezova *et al.,* 2019*)*.

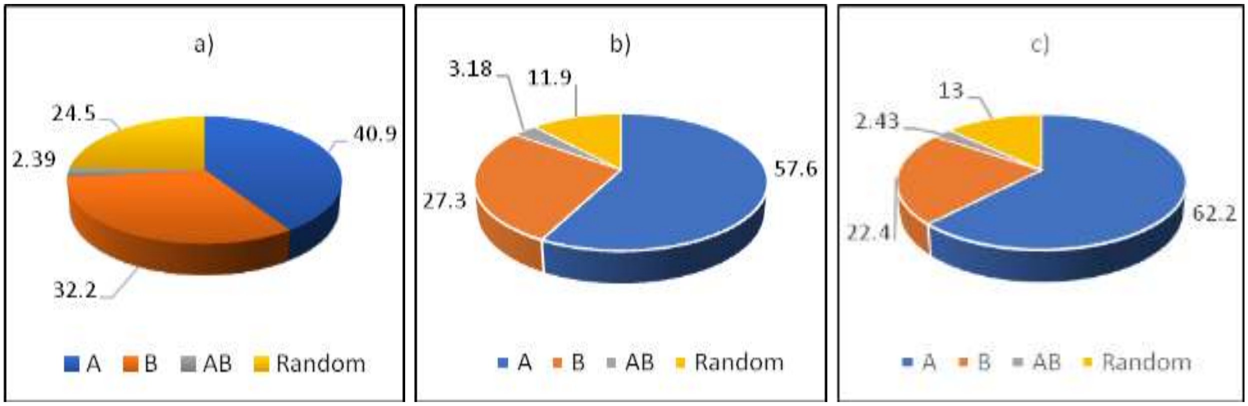

Figure 4. R of two-way ANOVA of four wheat and barley samples: (a) 2018, (b) 2019, (c) 2020, where A – cultivar, B – soil cultivation method, AB – cultivar and soil cultivation method.

Data processing using a two-factor analysis of variance showed a significant influence of the cultivars, tillage methods, and the interaction of cultivars and tillage methods (Figure 4). The share of cultivars' contribution in forming the grain yield of spring wheat and barley was 40.9%–62.2%, and based on the crop season, the share of the used tillage method was 22.4%–32.2%, and the portion of the interaction of both factors was 2.39%–3.18%. The grain yield formation depended more on the cultivars, and the dependence increased more due to the weather conditions during the crop season.

CONCLUSIONS

In the drylands of Southeast Kazakhstan, a high yield resulted in the promising cultivar number spring wheat and the spring barley cultivar Symbat of the CIASA selection, provided with plowing to 20–22 cm. The use of no-till contributed to forming an excellent soil aggregate state (65%–69%) of the arable soil layer with spring wheat and barley during the crop season. The content of water-resistant aggregates was the highest in the variants with no-till (19.3%–21.8%), indicating unsatisfactory water resistance of the soil structure. Based on the two-factor ANOVA analysis, the contribution of cultivars in shaping the grain yield of spring wheat and barley depended on the crop season (40.9%–62.2%), and the tillage methods share was 22.4%–32.2%. Thus, the grain yield formation depended more on the studied crops and cultivars. The yield dependence has only increased over the years due to varied weather conditions during the crop seasons.

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