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## HUMUS BALANCE IN ARABLE SOILS OF KAZAKHSTAN

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### SUMMARY

Overall, the proportion of soils with a stable humus status declined from 57% (2016) to 22% (2022), emphasizing widespread soil organic matter degradation in the Republic of Kazakhstan. The following study aimed to evaluate the humus balance of arable soils and substantiate approaches for restoring soil fertility. Humus balance calculations for 2022–2024 were according to yield statistics, the normative coefficient of organic matter removal, and the humification coefficient of crop residues. The results showed a consistently negative humus balance across major crops, ranging from  $-0.6$  to  $-1.4$  t ha<sup>-1</sup> yr<sup>-1</sup>. The greater losses emerged under row crops, vegetables, and cotton, while maize, rice, and perennial grasses exhibited lower depletion rates. The results highlighted the urgent need for organic matter replenishment through crop residue retention, organic fertilization, green manures, and soil-conserving technologies.

**Keywords:** Humus balance, soil organic matter, soil fertility, sustainable agriculture, Kazakhstan

**Key findings:** In Kazakhstan's agriculture, the negative humus balance was evident under most primary crops, except for perennial grasses, which ranged from  $-0.6$  to  $-1.2$  t ha<sup>-1</sup> yr<sup>-1</sup>. The greater humus losses occurred under row and vegetable crops, reaching  $-1.4$  t ha<sup>-1</sup> yr<sup>-1</sup>, whereas under maize and rice crops, the lowest recorded loss was  $-0.6$  t ha<sup>-1</sup> yr<sup>-1</sup>.

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## INTRODUCTION

In arable soils of Kazakhstan, the decline in soil organic matter and humus content has become an increasingly critical problem under intensifying anthropogenic pressure and ongoing climate change. Rising air temperatures, increased frequency of droughts, and extreme hydrothermal events further accelerate organic matter mineralization and reduce biomass inputs, which eventually lead to considerable depletion in humus. Long-term studies have revealed widespread land degradation and desertification processes in Kazakhstan under the combined influence of climatic aridization and anthropogenic pressure (Hu *et al.*, 2020; Turebayeva *et al.*, 2022; Ussipbayev *et al.*, 2025). The problem of humus reduction is especially prevalent in the regions of intensive agriculture, including Northern and Southeastern Kazakhstan. Methods, such as simplified crop rotation, insufficient return of crop residues, limited availability of organic fertilizers, and imbalanced fertilization systems, contribute to the persistent negative balance of humus (Blanco-Canqui and Lal, 2009; Pronko *et al.*, 2021; Lodygin *et al.*, 2023). According to the Transparency Report of Kazakhstan, the soil's proportion with a stable humus content decreased from 57% (2016) to 22% (2022), reflecting a large-scale depletion of soil organic carbon reserves and intensification of soil degradation processes.

The humus losses reduced soil fertility and crop productivity, as well as weakened the agroecosystem's resilience to climate change. Soil organic matter depletion proved associated with increased CO<sub>2</sub> emissions, disruption of nitrogen and phosphorus cycles, reduced water-holding capacity, and loss in soil structural stability (Kogut, 2012). Under the arid and semi-arid environmental conditions of Central Asia, where organic matter mineralization rates were inherently high, maintaining optimal humus levels is a key factor in ensuring sustainable crop production.

Humus is a central determinant of soil fertility, influencing physical, chemical, and biological properties of soil, including aggregation, buffering capacity, nutrient

retention, and microbial activity. The establishment of basic concepts of humus formation, transformation of plant residues, and methodologies for assessment of the humus balance has succeeded in classical and modern studies (Velten *et al.*, 2015; Chernova *et al.*, 2021). Such past research emphasized the role of crop composition, organic amendments, and agronomic practices in regulating soil organic matter dynamics.

Humus degradation intensified, following large-scale cultivation of virgin and fallow lands during the 1950s–1960s in Kazakhstan. Continuous intensive tillage, monocropping, and insufficient application of organic fertilizers resulted in substantial humus losses in chernozem, chestnut, dark chestnut, and sierozem soils (Hu *et al.*, 2020). The Ministry of Agriculture of Kazakhstan's recent analytical reports revealed a significant proportion of arable lands continue to experience a negative humus balance, suggesting that existing agricultural technologies remain insufficient for sustainable soil management.

International initiatives, such as the Food and Agriculture Organization (FAO) program, the '4 per 1000 Initiative,' and Intergovernmental Panel on Climate Change (IPCC) climate strategies, emphasized the restoration of soil carbon stocks as a cornerstone of climate-resilient agriculture (FAO, 2021; Bosma and Hein, 2023). According to ISRIC–World Soil Information (2020), Kazakhstan's classification as a region reached a high risk of soil organic carbon loss, highlighting the urgency of adopting scientifically grounded soil conservation measures.

Sustainable agriculture with modern approaches prioritized reduced and zero tillage, retention of crop residues, cover cropping, mulching, integrated application of organic and mineral fertilizers, and expansion of perennial grasses in crop rotation (Blanco-Canqui and Lal, 2009; FAO, 2021). In greater analogy with national strategies for carbon-neutral development, the recognition of enhanced soil organic carbon stocks emerged as an essential component of Kazakhstan's agro-environmental policy.

Therefore, based on the above discussion, the promising study aimed to evaluate the present humus balance in Kazakhstan's agriculture. It also sought to identify crop-related variations in humus depletion and substantiate practical approaches for restoring soil organic matter under agricultural intensification and increased climatic stress conditions.

## MATERIALS AND METHODS

In this research, the humus balance calculation used generally accepted methodological approaches, which were applied to six major agricultural regions of Kazakhstan: North Kazakhstan, Akmola, East Kazakhstan, Zhambyl, Almaty, and Turkestan. All calculations depended on average indicators for the period of 2022–2024. Humus input estimation from the mass of postharvest and root residues considered crop-specific humification coefficients, while determining humus losses was according to standard mineralization rates (Markovska *et al.*, 2020). Yield data, nutrient removal rates, and mineralization coefficients entailed adaptation to the existing soil and environmental conditions using official statistics of the Ministry of Agriculture and the Bureau of National Statistics, Kazakhstan (Tokbergenova *et al.*, 2024).

The humus mineralization estimation relied on nitrogen utilization during crop cultivation. Assuming nitrogen removal with the harvested yield corresponded to plant uptake, adjusting it for biological nitrogen fixation in leguminous crops occurred. An assumption also existed that biological nitrogen fixation provides approximately 70% of nitrogen in perennial legumes, 60% in annual grain and forage legumes, and 37% in mixtures of annual forage crops such as vetch–oat–pea. For different crops, applying the normative values of annual humus mineralization took place in the calculations (Mikhaylov, 2001). These norms account for both direct mineralization processes and crop-

induced enhancement of humus decomposition associated with root morphology, crop density, and tillage intensity.

The application of correction coefficients to nitrogen removal values accounted for soil texture and crop type. The coefficients for soil texture were heavy loam (0.8), medium loam (1.0), light loam (1.2), sandy loam (1.4), and sand (1.8). Crop-specific coefficients were the perennial grasses (1.0), cereals and other annual crops with continuous soil cover (1.2), and row crops (1.6). We assumed that soil-derived nitrogen (associated with humus mineralization) constitutes 50%–60% of total nitrogen removal by the different crops, based on mineral fertilizer application rates, since fertilizer application appeared closely linked to yield levels, with the share of soil nitrogen determined relative to crop productivity. Humus mineralization calculation was by multiplying soil nitrogen removal by a conversion coefficient of 20 (Markovska *et al.*, 2020).

The non-inclusion of losses of humus under bare fallow was due to the lack of official statistics on fallow area. However, according to published data, up to 2 t ha<sup>-1</sup> of humus may mineralize annually under bare fallow conditions. According to published sources (Belgibayev, 2021), anthropogenic impacts under prolonged agricultural use result in annual humus mineralization, ranging from 0.5 to 1.6 t/ha, depending on the soil type and subtype, whereas under bare fallow conditions, it may reach an average of 2 t/ha. At the same time, as noted above, in soils ranging from chernozems to serozems, the changes in either direction amount to 1.5–2.5 t/ha. For the purposes of nationwide assessment, erosion coefficients differentiated by various crops were inapplicable, assuming relatively flat topography of most arable lands. Nevertheless, erosion processes, particularly under prolonged bare fallow and row crops, can further intensify humus losses. With slopes of 2°–4°, erosion may account for up to 15% of total humus losses, while mineralization remains the dominant factor (Kunanbayev *et al.*, 2022).

Therefore, the calculated humus balance should be potential conservative estimates, and the actual losses may be higher in areas prone to wind and water erosion, especially in Southern Kazakhstan.

## RESULTS AND DISCUSSION

Kazakhstan's major agricultural regions exhibited a negative humus balance due to insufficient organic matter inputs under intensive land utilization (Almanova *et al.*, 2023). In Northern Kazakhstan, widespread soil dehumification has been ascribable to long-term plowing and limited residue return (Toktar *et al.*, 2019). Reports on decline in key fertility indicators of soil under prolonged agricultural exploitation have also prevailed (Almanova *et al.*, 2023). National research revealed that annual humus losses from arable lands range from 0.5 to 1.4 t ha<sup>-1</sup>, based on the soil-climatic zone and cultivation practices (Baitulin and Usenov, 2020; Karpenko and Agibaev, 2023), consistent with the trends observed in this study (Figure 1).

Significant land-use variations occurred between 1990 and 2010 in Kazakhstan, including a substantial reduction in arable land area and fertilizer application. Previous studies documented that cropland abandonment and decreased organic matter inputs markedly affected soil organic carbon dynamics in the steppe regions of Kazakhstan (Rolinski *et al.*, 2021). These structural variations in land utilization developed long-term prerequisites for a persistent negative balance of humus. Past studies also revealed arable land regions with reduced fertilizer inputs showed accelerated soil organic matter depletion (Toktar *et al.*, 2019, Rolinski *et al.*, 2021,).

These processes, along with violations of agrotechnical practices and the predominance of cereal monocultures, hastened the deterioration of soil properties and soil degradation. Previous studies revealed that limited diversity in crop rotation and reduced application of organic amendments resulted in a practical decline in physical, physicochemical, and biological indicators in

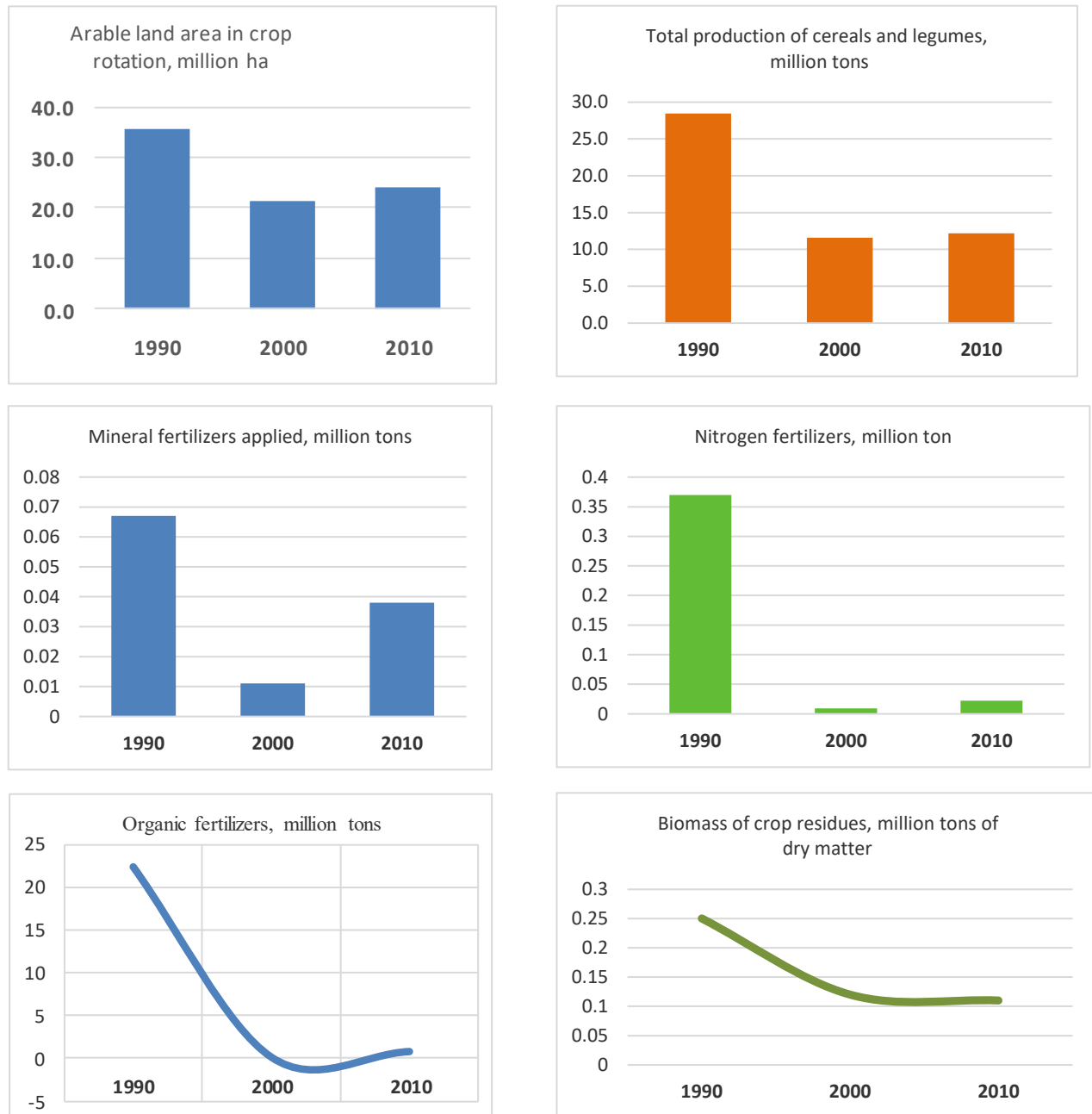
the steppe soil zone of Kazakhstan (Belgibayev, 2021). As a consequence, a substantial reduction in overall soil fertility and agroecosystem stability ensued, consistent with the reported decrease in soil productivity under intensive monoculture systems.

Table 1 presents the generalized data on humus balance for the studied regions averaged for 2022–2024. The northern and central regions experience the largest absolute losses of soil organic matter due to intensive cultivation and arid climate (Hu *et al.*, 2020). Latest results confirmed that chernozem soil zones exhibited losses of 0.5–1.0 t ha<sup>-1</sup> annually, while the southern regions, despite lower absolute losses, maintain a consistently negative balance.

In southern regions, due to initially smaller reserves and somewhat higher fertilizer inputs, the humus losses were lower; however, the balance remained negative. In individual farms, achieving near-equilibrium humus balance was successful through intensive application of organic and mineral fertilizers. Overall, approximately 75% of arable lands showed the signs of degradation, with 62% of surveyed areas characterized by low humus content in Kazakhstan.

Based on the applied current methodology, calculating the humus balance for major crops cultivated in Kazakhstan during 2022–2024 continued, averaging over three years (Figure 2). Row crops, technical crops, and vegetables tended to be the most humus-depleting crops. Intensive inter-row cultivation and minimal residue retention in these crops accelerate organic matter mineralization (Pronko *et al.*, 2021), likely referring to the large humus deficits observed in potatoes, melons, tobacco, vegetables, and cotton crops in this study.

Root crops and sunflowers also showed pronounced humus depletion. Even high-yielding root crops often fail to compensate for humus losses, as harvested biomass removes the substantial organic carbon (Kogut, 2012). These findings were greatly analogous to the presented observations for sugar beet and sunflower, where residue inputs were insufficient to offset mineralization.



**Figure 1.** Trends in arable land use, crop production, fertilizer use, and crop-residue biomass in Kazakhstan during 1990–2010.

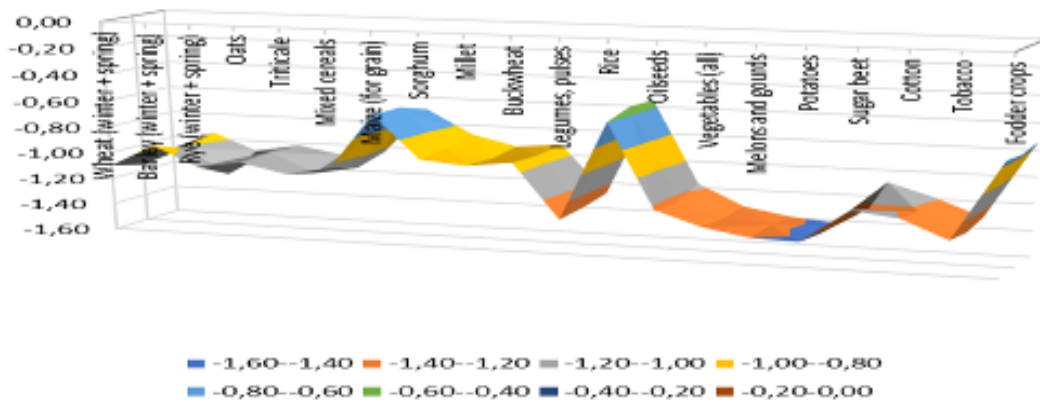
Cereal crops primarily exhibited moderately negative humus balances. Straw removal substantially reduces soil organic carbon replenishment in cereal-based cropping systems (Blanco-Canqui and Lal, 2009). The study results revealed that despite considerable straw and root biomass, cereal

residues alone cannot compensate for annual humus mineralization under the prevailing field environmental conditions.

Grain legumes exhibited humus deficits similar to cereals. Although biological nitrogen fixation enhanced nitrogen availability, it does not necessarily increase humus accumulation

**Table 1.** Annual humus balance in major agricultural regions of Kazakhstan, 2022–2024 (generalized data, t ha<sup>-1</sup> yr<sup>-1</sup>).

Region	Main soil types (average humus %)	Input (t ha <sup>-1</sup> yr <sup>-1</sup> )	Losses (t ha <sup>-1</sup> yr <sup>-1</sup> )	Balance (t ha <sup>-1</sup> yr <sup>-1</sup> )
North Kazakhstan	Ordinary and leached Chernozems (4%–5%)	0.5–0.8 (crop residues; little manure)	1.0–1.2 (grain harvest removal, mineralization; wind erosion)	Negative (–0.5 –0.7)
Akmola	Southern Chernozems, Dark Chestnut soils (3%)	0.4–0.6 (residues; minimal organics)	0.8–1.0 (grain harvest removal; wind erosion)	Negative (–0.3 –0.5)
East Kazakhstan	Dark Chestnut soils, Chernozems (3%–4%)	0.5 (grain residues, mixed herbs)	0.8 (crop removal; partial water erosion on slopes)	Negative (–0.3 –0.5)
Zhambyl	Sierozems, Light Chestnut soils (2%)	0.3–0.4 (stubble residues; small amounts of manure on irrigated lands)	0.6–0.7 (crop removal, accelerated decomposition on irrigation)	Negative (–0.2–0.3)
Almaty	Foothill Chernozems, Chestnut soils; plain Sierozems (1%–2%)	0.4 (crop residues; some manure in vegetable farming)	0.5–0.6 (double cropping under irrigation without compensation; erosion)	Negative (–0.1 –0.2)
Turkestan	Sierozems (gray desert soils); foothill Chernozems (<2%)	0.3 (minimal residues after cotton and melons; little manure)	0.6–0.8 (large cotton/grain harvest removal; rapid decomposition under heat and irrigation)	Negative (–0.3 –0.5)



**Figure 2.** Annual humus balance (t ha<sup>-1</sup> yr<sup>-1</sup>) in Kazakhstan’s agriculture by major crops (2022–2024).

(Velten *et al.*, 2015). Previous studies reported that the rapid decomposition of legume residues likely explains their limited effect on humus balance in this analysis. Grain, maize, and rice crops were the most recognized, least humus-depleting annual crops. High residue return under maize crops improved soil organic matter dynamics when retaining residues (Kunanbayev *et al.*, 2022). In rice, anaerobic

soil conditions slow down the residue decomposition, leading to reduced humus losses (Bierke *et al.*, 2008). An explanation for this could be that the relatively low humus losses observed in this case are likely related to the factors mentioned above and to the specific agrotechnological features of cultivating these crops in Southern Kazakhstan. In particular, maize and rice are

the predominantly grown crops under irrigated conditions, showing a general association with higher fertilizer inputs than rainfed systems, and this may also have contributed to the lower intensity of soil dehumification.

Perennial grasses and forage crops showed the highest potential for humus stabilization. No-till systems combined with perennial crops considerably enhanced the soil organic matter (Turebayeva et al., 2022). The latest results confirmed that the increasing proportion of perennial grasses in crop rotation emerged as an effective strategy for sustaining humus balance in Kazakhstan soils. Governing the formation of humus balance in arable soils is both by agrotechnological practices and the genetically determined characteristics of cultivated crops. Aboveground biomass production and the quality of postharvest residues are under substantial genetic control.

The C:N ratio, lignin content, and structural polymers largely determine the rate of residue decomposition and their contribution to humus formation (Bierke et al., 2008). Genotypes' characterization via increased straw production, provided that the residues remained in the field, can improve the balance of soil organic matter. Of particular importance are perennial crops, which develop considerable root biomass and maintain continuous plant cover. Meta-analytical studies have confirmed their positive role in the accumulation of soil organic carbon (Siddique et al., 2023). Therefore, integrating breeding programs to enhance root biomass and optimize the quality of plant residues could be a strategic approach to regulating humus balance and improving the sustainability of agroecosystems.

## CONCLUSIONS

Arable soils of Kazakhstan succeeded in their characterization by a predominantly negative humus balance under almost all major crops, with losses ranging from  $-0.6$  to  $-1.2$  t ha<sup>-1</sup> yr<sup>-1</sup>. However, the greatest humus depletion occurred under row crops and vegetables (up to  $-1.4$  t ha<sup>-1</sup> yr<sup>-1</sup>), whereas the lowest losses were evident under maize and rice. Prevention

of humus losses caused by erosion is critically important, as a single dust storm can remove a soil layer containing humus accumulated over several decades. Compensation of a humus deficit ( $0.5$ – $0.7$  t ha<sup>-1</sup>) requires substantial inputs of organic matter. For instance, a deficit of about  $0.7$  t ha<sup>-1</sup> under cereal crops can be offset by applying approximately  $9$  t ha<sup>-1</sup> of manure or by retaining at least  $4$  t ha<sup>-1</sup> of crop residues. Reducing annual humus losses is possible through increased use of organic fertilizers and green manures, retaining crop residues, expanding perennial grasses in crop rotations, and further assessing reduced tillage technologies under the soil and climatic conditions of Kazakhstan.

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