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Increase in Productivity of Chestnut Soils on Irrigated Lands of Northern and Central Kazakhstan

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Abstract: Natural conditions in North and Central Kazakhstan and the energy potential of chestnut soil testify to the efficiency of agriculture, especially on irrigated lands. The humus horizon of chestnut soils is 35–50 cm, and the humus content is 3.0–3.5%. The majority of the humus (75%) is contained in a half-meter layer, which emphasizes the short humus level. The phosphorus content, both gross and mobile, is very low at 0.98–0.031%. Potassium is in elevated amounts. Soils are most susceptible to the application of nitrogen–phosphorus fertilizers. According to the mechanical composition, chestnut soils are predominantly lightly loamy, light clays with substrates of souses. Salinization is low, with a salt content in the 0–100 cm soil layer of 0.10–0.20%. The mass of the arable soil layer is 1.3–1.4 g/cm^3. Deep plowing and loosening of soils improve the water and nutrition regime, creating good conditions for arid agriculture. With deep autumn plowing up to 30 cm, the accumulation of sediment and spring meltwater reaches 1200–1500 m^3/ha more than in spring disposal. Deep plowing ensures absorption of irrigation water, eliminates run-off during irrigation, and reduces the number of crops requiring extra irrigation. In an average dry year, at 50% water availability and 70% soil moisture content (MC), the number of irrigations is 4, and the irrigation rate is 300–470 m^3/ha; at 60% MC, 2 irrigations are performed, and the irrigation rate is 600–650 m^3/ha. On irrigated land, the yield of cereals is 2.8–2.6 t/ha; perennial grasses, 3.0–4.5 t/ha; potatoes, 23.2–24.1 t/ha; carrots, 35.0–40.0 t/ha; and cabbage, 50.0–75.0 t/ha.

Keywords: water regime; food regime; irrigation rate; productivity; irrigated agriculture; water consumption; moisture availability; water permeability

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1. Introduction

Sustainable agricultural development and food and environmental security in Kazakhstan are closely linked to the rational and efficient use of soils [1]. Due to the approved norms of inefficient use of agricultural land in Kazakhstan, the need to improve the mechanisms of agricultural land turnover management requires regulation of land relations [2]. In addition, Kazakhstan has a powerful tool for prompt and reliable monitoring of effective land management, agricultural production, and economic activity. Preplanting of basic nutrients on the main types of soils has a significant impact on the development of plant biomass [3,4]. It allows establishing the efficiency of fertilizers used in certain crops, determining the relationship between the chemical composition of soils, plants and crops, and developing a comprehensive method for optimizing the mineral nutrition of plants [5].

In this regard, the first methods of soil conservation were developed in northern Kazakhstan in the 1960s. Farming systems were based on the production of grain in a fallow rotation, with rotated soils being cultivated [6]. Currently, many components of this system are being revised to increase soil efficiency and sustainability. The climatic conditions of Central and Northwest Kazakhstan are harsh and arid, with sharp continentality and strong winds. The probability of dry years in the steppe zone is 38% [7–10]. The territory in question is characterized by a typical dry spring-summer period and rare dry autumn and wind-dry periods. Drought damage depends on its duration and on the autumn and early spring moisture reserves in the soil. Plants do not suffer from a lack of heat during the entire growing season, with a radiation value of 45–50 kcal/cm^2/year, but often suffer from a lack of moisture, which is most acutely felt during periods of atmospheric drought [11–13].

The precipitation volume during the vegetation season in the dry steppe zone ranges from 110 to 130 mm; however, the maximum precipitation shifts to the early spring months. Sown spring wheat already in the budding phase suffers from a lack of moisture in the soil. By this time, the moisture reserves are 10–20 mm in the arable layer, 30–50 mm in the half-meter layer, and 50–100 mm in the meter layer. During heading, flowering, and grain filling, the moisture deficit in the soil increases. Grain filling occurs during dry wind periods lasting from 3 to 10 days and with a chance of 50–70%. Moreover, plants in the area under consideration experience a lack of productive moisture in a meter-deep soil layer, not only in a moderately dry year (75% of water supply), but also in an average moist year. A specific feature of the steppe zone of Kazakhstan is that the moisture deficit in the soil is observed not in general during the growing season, but only at particular periods. In the dry steppe area during the sowing period, the optimal moisture supply is observed once every 5 years. In the arid-steppe zone, 9 years out of 10 [14–16].

According to the long-term climatic data of the Pavlodar meteorological station, the shortage of water supply for wheat is observed from May to September, with a relative humidity of 40%, and the total water consumption exceeds precipitation by 10–30% (Figure 1) [17].

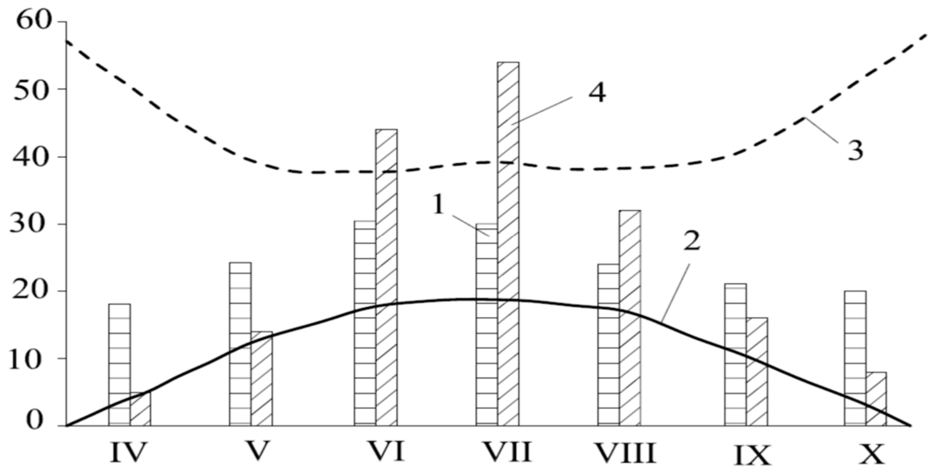

Figure 1. Long-term climatic data of the Pavlodar weather station (1930–2022) average monthly data: 1—precipitation, mm; 2—air temperature, C; 3—relative humidity at 13 h, 4—water consumption of wheat.

Agro-climatic indicators, their quantitative and qualitative characteristics, and the assessment of soil resources in northern and central Kazakhstan indicate the feasibility of using irrigation reclamation, which provides optimal water, nutrient, and air conditions for soil [10]. According to the mechanical composition, chestnut soils are predominantly light loamy, with underlying sandy loams, and the bulk density is 1.3–1.4 g/cm^3. Despite the light mechanical composition, there are many silty particles, the content of which reaches 15–20%. These mineral colloids play a certain role in the formation of water-stable microaggregates. The soil absorption capacity varies from 13 to 15 mg-equivalent per 100 g. Calcium dominates [17].

The salt volume does not exceed one hundredth of a percent. Sulfates dominate over chlorides. Productive moisture in humus horizons accounts for 12–17% of the porosity. Moisture reserves at wilting moisture in sandy, light, and medium loamy soils in the 0–100 cm layer are 60, 74, and 88, respectively, or an average of 38% MC. The moisture capacity in the soil layer mainly depends on the mechanical composition of the genetic horizons. In the humus horizon of medium loamy soils, it is 16–20% of the soil mass; in sandy loamy soils, it decreases to 10–12%. Productive moisture in humus horizons is 12–22% of soil porosity [8]. The surface layer of soils has a high water permeability; therefore, sprinkling irrigation is used on all types of soils [17]. The nutrient ratio (N:P) in the upper part of the soil layer somewhat reduces the nitrogen supply of plants and increases the role of phosphorus in their nutrition. With the growth of plants, their nutrition increases in the lower part of the arable layer, which is more constant in moisture content and is not subject to sharp fluctuations; it is much more stable in conditions of arid agriculture [18].

Research hypothesis: This study suggests that loosening and plowing the land to a depth of 25–30 cm during reclamation improves the physical and aquatic properties of the soil, water and feeding regimes, feeding conditions, and the development of agricultural plants in dry farming conditions.

The object of the study is soil fertility in Chestnut soils of irrigated lands in Northern and Central Kazakhstan [1,5,8] and productivity of agricultural crops [10,14]. The purpose of the study was to review the literature [1,5,8,10,11,14,17] and, through our own experience, to determine whether plowing the land to a depth of 25–30 cm on irrigated areas of Chestnut soils in northern and central Kazakhstan can increase crop yields and energy efficiency.

2. Materials and Methods

The study started with obtaining soil samples to determine the steppe moisture content of chestnut soils in irrigated lands of northern and central Kazakhstan. Soil sampling was conducted in Pavlodar and Karaganda oblasts on fields with a 0–100 cm soil layer (in 2022) in spring before fertilization and sowing and in autumn after harvesting. Three samples with a field size of 2 m × 100 m × 3 = 600 m^2 = 0.6 ha were created. The total field area was 0.6 × 3 = 1.8 ha. Soil samples were taken with a soil borer (Figure 2).

Figure 2. Manual soil sampling from a grain field. (**a**) In the spring before fertilizing. (**b**) Autumn after harvesting.

One-third of the samples were filled with soil and sealed with a lid. Field soil moisture surveys were carried out in certified laboratories of the U.U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistry (Almaty, Kazakhstan). The aluminum beaker was reweighed in the laboratory and then placed in the drying cabinet at T = 105 °C and dried to a stable mass (8 h). The lid of the closed beaker was then removed and placed on the bottom of the beaker, cooled and measured in a desiccator. Field soil moisture was calculated using the formula below:

$$W = \frac{100 \times a}{b}$$

where W represents the field humidity (%); a represents the mass of evaporated water (g); and b represents the mass of dry soil (g) [19].

The field experiment was carried out on Chestnut sails in the "Sergey" farm of the Aksu irrigation basin of the Pavlodar region. The area of each variant was 100 m^2 (length 50 m = width 2 m) of 3-fold repetition. There is a 1.5 m wide protective platform between the experimental fields (Figure 3).

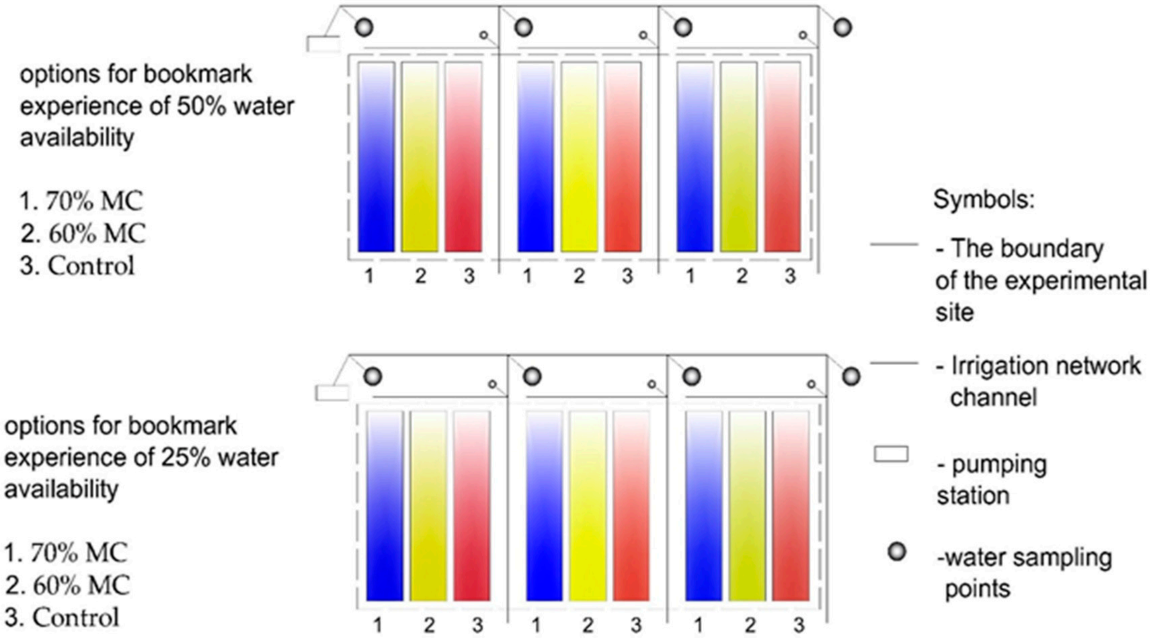

Figure 3. Scheme of the bookmark of experience on the farm "Sergey" cultivated spring wheat.

The technology of grain and vegetable crop cultivation was studied with deep loosening and plowing of 30 cm, soil moisture of 60% MC and 70% MC, 25% in a wet year and 50% in a medium dry year with precipitation. Vegetable crops were cultivated at a soil moisture of 70% MC. The dynamics of changes in the moisture content of the active soil layer were determined by soil sampling. Watering was carried out by a DDA-100MA sprinkler machine.

The rate of irrigation and the indices of photosynthetic activity (FAR) of radiation were determined by the formula below:

$$m = 100 \times H \times \gamma \times (HB - \beta 0)\ m^3/ha$$

where H represents the soil moisturizing layer, H = 0.4–1.0 m; γ represents the volumetric mass of the soil (t/m^3); HB-free represents the water capacity of soil (%); and β0 represents the soil moisture before watering (%) [20].

3. Results

The field study showed that photosynthetically active radiation (PAR) F, crop yields, and water consumption always increased in hot years. In the hot year 2022, wheat yield and water consumption were higher than in the cold year 2021 (Figure 4).

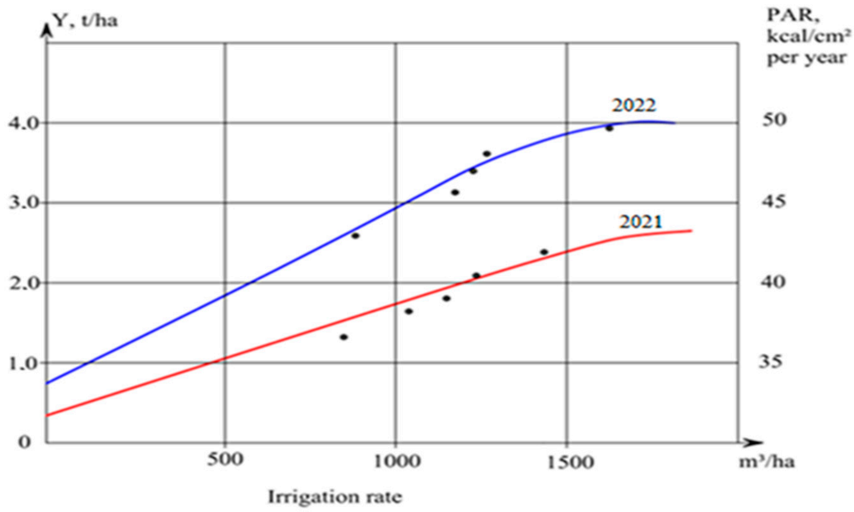

Figure 4. Dependence of spring wheat crop on the irrigation rate and photosynthetic activity of radiation (PAR) [17].

Soil water permeability depends on its cultivation, and deep loosening and plowing of soils 25–30 cm ensures rapid absorption of thawed, rain, irrigation water, and eliminates surface runoff, as well as surface waterlogging of soils during irrigation (Figure 5) [8].

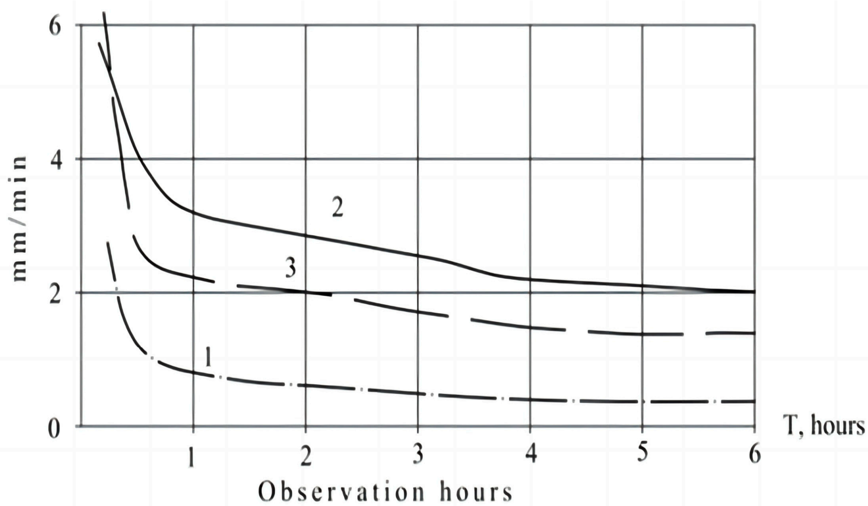

Figure 5. Water permeability of dark chestnut carbonate soil depending on soil cultivation: 1—disking; 2—loosening deep; 3—plowing normal [8].

During disking, the soil is loosened by only 8–12 cm of the upper layers of the soil, with deep plowing by 30 cm, while the water and food regime improves in the soil, precipitation and spring meltwater accumulate by 1200–1500 m^3/ha more than during spring disking. Deep plowing ensures the absorption of irrigation water, eliminates surface runoff during irrigation, and reduces the number of irrigations of cultivated crops [8,12].

Agricultural crops in the Pavlodar region are cultivated mainly by local irrigation systems engineered with wide-reach sprinkler machines “Volzhanka”, “Frigate”, “Dnepr”, working with water intake from hydrants of high-pressure closed pipes and sprinkler machines DDA-100MA, DDN-70 (100) and “Kuban” feeding from open sprinklers, into which water is supplied through a network of low- and medium-pressure pipes and trough channels.

In the area of the Irtysh–Karaganda canal, irrigated agriculture occupies a significant place in the agricultural production of the Pavlodar and Karaganda regions. In recent years, 35% of potatoes and vegetables in the Karaganda region and 24% in the Pavlodar region were produced on these lands. The availability of land and water resources makes it possible to support highly efficient irrigated agriculture and to obtain high and stable yields of agricultural crops [8,17]. The yield of vegetable crops on irrigated lands with a soil moisture of 65% MC is 35.1–40.2 t/ha, including carrots 35.0–40.0 t/ha, table beet 25.0–27.5 t/ha, cabbage 50.0–75.0 t/ha, and potatoes 23.2–24.1 t/ha (Table 1).

Table 1. Yield of vegetable crops on irrigated lands of Aksu district, Pavlodar region.

Years	Vegetables		Carrot		Table Beet		Cabbage		Potatoes	
	Area Hectare	Yield t/ha	Area Hectare	Yield t/ha	Area Hectare	Yield t/ha	Area Hectare	Yield t/ha	Area Hectare	Yield t/ha
2021	102	40.2	90	40.0	8	25.0	4	75.0	28.8	23.2
2022	103.3	35.1	90	35.0	9	27.5	4	50.0	27.8	24.1

The total moisture consumption in irrigated areas is 3000–3550 m^3/ha in average dry years and 3170–3700 m^3/ha in wet years, with slight fluctuations in different humidity limits before irrigation (Table 2).

Table 2. Elements of water balance, evaporation and productivity of spring wheat in the farm “Sergey” of the Aksu irrigation basin.

% Humidity Sufficiency	Experimental Variants	Elements of Water Balance, mm				Actual Evapotranspiration, mm	Yield, t/ha	Water Consumption for the Formation of a Unit of Production, m^3/t	
		Precipitation	Irrigation rate	Soil Moisture Reserve	The Amount of Groundwater Use			Total Water Consumption	Irrigation Water
50	70% MC	116.7	149	10	41	317	2.6	1270	600
	60% MC	116.7	125	21	39	300	2.3	1360	570
	Control	116.7	-	79	28	215	1.1	1950	-
25	70% MC	200	55	67	48	370	2.8	1320	200
	60% MC	200	40	69	46	355	2.7	1310	150
	Control	200	-	73	41	314	1.5	1960	-

To maintain the moisture content of the active soil layer at least 70% MC, it will be necessary to carry out two irrigations in a wet year (25% availability) and four irrigations in the average water deficient (50% availability) years, with irrigation norms of 550 m^3/ha and 1490 m^3/ha, respectively (Table 3). Moreover, the irrigation norm in a wet year serves only as an addition to the precipitation that fell during the growing season in the amount of 120 mm. In the average dry year, irrigation coincided with the main phases of plant development: tillering, tubing, earing, grain formation, and precipitation in the amount of 70 mm during this period allowed an increase in the moisture reserves of the soil during the irrigation periods.

Table 3. Irrigation regime of spring wheat at the experimental site.

% Humidity Sufficiency	Prior to Irrigation Humidity Threshold, %	Number of Irrigations on MC	Number of Days between Irrigations	Irrigation Volume and Date				Irrigation Rate, m^3/ha
				1	2	3	4	
25% (wet year)	70	2	11	300 11.06	250 22.06	-	-	550
	60	1		400 12.06	-	-	-	400
50% (average year)	70	4	15–17	360 6.06	470 23.06	360 8.07	300 23.07	1490
	60	2	18	650 26.06	600			1250

To maintain the moisture content of the active soil layer at least 60% MC, two irrigations were performed in an average year, and one irrigation was performed in a wet year. Irrigation norms amount to 1250 m^3/ha and 400 m^3/ha for the years with sufficient precipitation. In the wet year, irrigation was carried out in the tillering phase, and in the average year, soil moisture dropped to 60% MC in the phase of earing and grain formation. In the remaining phases of plant development, the moisture level in the soil was replenished by precipitation.

4. Discussion

Experimental studies on chestnut soils of northern and central Kazakhstan have established that land reclamation and irrigated agriculture can provide highly efficient agricultural production, and deep loosening and plowing improve the physical and water properties of soils, water and food regimes, nutrition conditions, and the development of agricultural plants in arid agriculture. The destruction of compacted layers and their mixture with the arable layer noticeably improve the structure, increase the borehole and water permeability of soils, accumulation of precipitation and spring meltwater, their absorption, and the accumulation of large reserves of moisture compared to other methods of basic agriculture (Figure 6) [16,21,22].

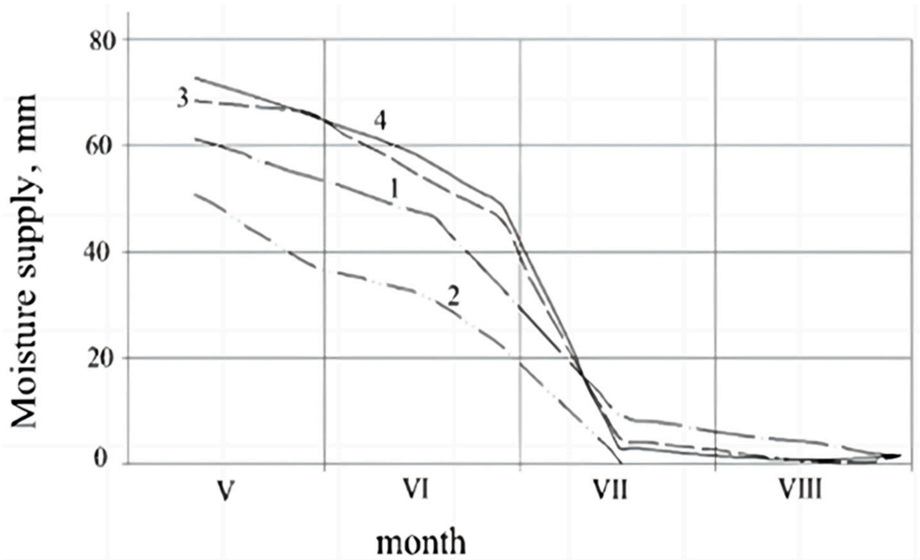

Figure 6. Dynamics of moisture available to plants (W) in dark-brown carbonate soil, depending on the treatment: 1—when disking (5 months-61 mm, 6 months-47 mm, 7 months-10 mm, 8 months-4 mm); 2—when loosening deep (5 months-52 mm, 6 months-31 mm, 7 months-0 mm); 3—when plowing normal (5 months-68 mm, 6 months-54 mm, 7 months-4 mm, 8 months-0 mm); 4—when plowing deep (5 months-74 mm, 6 months-58 mm, 7 months-3 mm, 8 months-0 mm).

The arable layer is characterized by a significant capacity, a two-tiered structure with vertical heterogeneity, the reverse of the natural profile of soils, and fertility potential and effectiveness, increasing from the surface to depth. The deep placement of the humus horizon and its more fertile part, as well as fertilizers, reduces the concentration and ratio of nutrients (N:P) in the upper part of the soil layer, somewhat reduces the nitrogen supply for plants and increases the role of phosphorus in their nutrition. With the growth of plants, their nutrition increases in the lower part of the arable layer, which is more constant in moisture content and is not subject to sharp fluctuations; it is much more stable in conditions of arid agriculture [5,18].

Plants develop a powerful and deep root system, and their active zone is located mainly in the lower, more fertile part of the arable layer. In this regard, they make much better use of the effective soil fertility, moisture, nutrients, and fertilizers applied [10].

Plowing of soils reduces the albedo value, which is accompanied by an increase in the radiation balance, the amount of photosynthetically active radiation (PAR), and the dryness index, which are determined by M.I. Budyko I = R/(Loc), where R is the radiation balance and Loc is the heat consumption for precipitation evaporation [23,24]. The values vary depending on the type of soil and vegetation cover; the sum of the active temperatures increases by 9–15%, the PAR by 5–11%, and the dryness index by 6–15%.

The yield of a particular crop, even with all controlled factors being at the optimum, will vary from year to year depending on the amount of photosynthetically active radiation (PAR)-F [17]. Therefore, indicators of reclamation regimes should be justified for a number of years with different levels of sufficiency, i.e., for long-term conditions [2].

The yield (Y) with 10, 25, 50, 75, and 90% provision for natural humidity is determined by the equation У = Oc − Epot (where Oc is the sum of precipitation and Epot is the total evaporation at optimal soil moisture), which allows us to estimate the average annual need for irrigation and changes in humus and nutrients. In addition, it becomes possible to change the amount of PAR and its effect on yield in a particular year. Уo = KiУ, where Уo is the yield of this crop in the long-term period, obtained at various testing sites, under optimal conditions and with standard agricultural technology; Ki is a coefficient that takes into account the variability of PAR over the years. Ki = Fp/F, where Fp is the number of PAR per year of p-th sufficiency, and F is the average annual value [8,17].

Thus, experimental studies have established that land reclamation on chestnut soils has two purposes: radical improvement of chestnut soil yield on irrigated lands and ecosystem component regulation of irrigated massifs, taking into account landscape agriculture. By providing optimal conditions for the development of agricultural crops, their yield can be increased several times. The task is to create optimal conditions for the development of cultivated plants on the fields in a given year. To achieve this, it is necessary to systematically eliminate negative and limiting factors and find and create the most favorable combination of climate and soil reclamation conditions [25–27].

Further development of agricultural production in the area under consideration involves consistent work on land reclamation, conservation and improvement of soil fertility, and the widespread introduction of scientifically based systems of irrigated agriculture. Therefore, along with technological improvement of irrigation systems, it is important to develop measures aimed at creating optimal water, nutrient, and salt regimes of soils that ensure high yields of cultivated crops [28,29].

5. Conclusions

The main conclusions of this paper are as follows:

- The climatic conditions of northern and central Kazakhstan are characterized by aridity and strong winds, and the probability of dry years is 38%. The negative impact of drought depends on its duration and moisture level in the soil. Deep loosening and plowing of soils to a depth of 30 cm increase the accumulation of precipitation and meltwater in the soil by 10–15% higher than normal plowing or disking;
- On irrigated lands with deep loosening and plowing, the yield of grain crops is 2.6–2.8 t/ha; vegetable crops, 35.1–40.2 t/ha; carrots, 35.0–40.0 t/ha; table beet, 25.0–27.5 t/ha; cabbage, 50.0–70.0 t/ha; and potatoes, 23.2–24.1 t/ha. With a soil moisture of 70% MC, four irrigations are carried out in an average dry year and two irrigations are carried out in a wet year; the watering rate is 300–470 m^3/ha and the irrigation rate is 550–1490 m^3/ha. Irrigation of irrigated lands is carried out by sprinkling: DDA-100MA, frigate, irrigation pipes to local water sources, and water intake from the Irtysh-Karaganda canal;
- As a result of the study, energy-efficient reclamation technology has been identified to increase soil fertility and crop yields in chestnut soils of irrigated lands in northern and central Kazakhstan. Soil water permeability directly depends on its tillage, and loosening and plowing the soil deeper than 25–30 cm ensures rapid absorption of melt, rain, irrigation water and eliminates surface runoff, as well as surface moisture in

irrigation. It also prevents the negative effects of drought on chestnut soils of irrigated land and maintains moisture by preventing prolonged dryness.

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