**Running title:** Modeling soil carbon accumulation

**Modeling soil carbon accumulation in irrigated agricultural systems**

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**Novelty statement**

This study aims to determine the impact of irrigation rates on soil carbon dynamics using agricultural system modeling. The results of this study portray the carbon cycle under the current climate change conditions and thus can be useful in agricultural management and food security projects. The present findings can be applied in irrigated and rainfed agriculture. Specifically, farmers may improve the productivity of irrigated lands in three different ways: through compliance with irrigation norms, by planting shelterbelts to provide water retention and a favorable microclimate, and by converting arable lands to fallow lands to restore fertility.

**Abstract**

This study aims to determine the impact of irrigation rates on soil carbon dynamics using agricultural system modeling. The simulations were conducted by LPJ-GUESS Education 3.0. The results were analyzed using the analogy method. Changes in soil carbon accumulation were quantified in three agricultural systems representing the desert, semi-desert and steppe zones of Russia. Results show an increase in soil carbon accumulation in all biomes and a decrease in ecosystem carbon exchange. These findings suggest that irrigation rates developed for desert, semi-desert and steppe biomes were effective. The results of this study can be applied in irrigated and rainfed agriculture.

**Keywords**: agroecosystem modeling, soil carbon, fertility, humus, irrigation, agronomy, soil science

**Introduction**

Countries with arid climates tend to irrigate their croplands, but this requires the development of methods for restoring soil carbon restoration. To solve this problem, the multifunctional agricultural systems are simulated. Unlike field or laboratory studies, simulations enable researchers to minimize their resources and time costs. The drawback is that simulations can overlook some contributory factors. The insufficient database of practical research findings lead to inaccuracy.

When simulating the recovery process of soil carbon, the entire carbon cycle must be considered. Carbon (C) is present in the biosphere in inorganic and inorganic forms, such as carbon dioxide and caustobioliths, respectively. In a simplified carbon cycle, plants absorb carbon dioxide from the atmosphere via photosynthesis as well as from water to produce organic matter. These plants are consumed by herbivorous animals, and herbivorous animals are in turn eaten by carnivores and humans. As heterotrophs carry out respiration, some amount of carbon dioxide cycles back into the atmosphere. Decomposition of dead plants and animal corpses by fungi and microorganisms also returns carbon into the atmosphere. Soil microorganisms and plant roots both participate in the soil respiration process, whereby they significantly increase the concentration of carbon dioxide in the troposphere (Nekos et al., 2010). As carbon dioxide interacts with rocks, carbon becomes part of various minerals. It returns into the atmosphere through natural rock weathering; this is especially true for carbonate minerals and those enriched with organic matter.

The concentration of carbon dioxide in the air increases due to human activities, such as fossil fuel combustion, transport operation, exploitation of hydrocarbon deposits, and more (Safranov, 2022). Carbon plays a direct role in soil fertility, for humus is formed by the incomplete decomposition of biomass. Under the influence of bacteria and fungi, humus can break down into carbon dioxide and mineral compounds (Nekos et al., 2010).

All of the above processes that cycle carbon between the air and the surface must be taken into account in the simulation. According to some researchers, the influence of the environment is extensive and complex, while the simulation models are too simplified; consequently, the results of the simulation and the actual experiment do not correspond to each other (Chen and Tian, 2007). Furthermore, some researchers highlight the need to investigate how soil carbon degradation can be prevented (Han and Li, 2018). The present study attempts to evaluate the impact of rationed irrigation on carbon recovery within the soil.

***Literature review***

There are many researchers across the world who investigated soil carbon recovery. According to their findings, soils in arid and semi-arid regions are prone to organic and inorganic soil carbon mineralization, which causes land degradation and desertification (Yin et al., 2011). Around 92% of the world's inorganic carbon is present in arid and semi-arid regions. In northwest China, soil inorganic carbon (SIC) pools are 2 to 5 times larger compared to organic carbon (SOC) stocks (Yin et al., 2011). The likely explanation is that the SOC content is indirectly affected by the physicochemical properties of the soil (Su et al., 2020). In particular, the lack of soil moisture and unfavorable physical and chemical conditions limit the activity of microorganisms, keeping the SOC content of cultivated lands low. The rate of SIC accumulation would be high in these conditions (Yin et al., 2011).

A three-year experimental study of carbon dioxide exchange in irrigated and rainfed agricultural systems found an increase in litter-C pools (including roots, stalks, leaves, and cobs) at irrigated continuous maize sites and in the irrigated maize-soybean rotation (by 230 and 200 g C m-2 year-1, respectively). The future soil carbon balance in these systems was reported to depend on the fate of carbon in these accumulating litter pools (Verma et al., 2005). More significant differences in SOC accumulation between rainfed and irrigated agricultural systems were detected in Colorado. Specifically, carbon accumulation rates were about three times higher in the irrigated system (Mosier et al., 2005).

Another experiment was devoted to measuring humus building efficiency. As reported, the carbon of plant material had a half-life between 39 and 54 days, animal manure had a half-life which ranged from 37 to 169 days, and for sewage sludge the half-life was 39 to 330 days. At the same time, all mature substrates and animal faeces demonstrated a higher humus building efficiency compared to plant materials except fine roots (Gasser et al., 2021).

Organic fertilizers cannot be used in large quantities. The same applies to mineral fertilizers and lime which farmers utilize to accelerate soil reclamation. The main task of farmers is to maximize profits from fertilizers while minimizing the negative impact on soil and groundwater (Ilves et al., 2020) In Poland, farmers are required to prepare a fertilization plan under the Nitrate Directive, which aims to protect waters from nitrates from agricultural sources. One of its provisions sets the upper limits for the amount of fertilizers that can be applied at 170 kg per hectare. These restrictions help to reduce greenhouse gas emissions (Syp et al., 2021). Thus, environmental requirements act as a factor affecting soil carbon accumulation.

Some researchers argue that for a more accurate simulation of soil carbon accumulation, the following must be taken into account: SOC fractions in fresh residues (Hong et al., 2021), air temperature and precipitation (Bolinder et al., 2012), and plant carbon input rate (Guo et al., 2006). The SOC cycling in the topsoil can be simulated using the RothC model. The inputs of this model include monthly precipitation and potential evapotranspiration (mm); average temperature (°C); clay content (%), DPM/RPM ratio; degree of soil cover (bare or vegetated); monthly crop carbon inputs from crop residues (t C ha-1); monthly manure inputs (t C ha-1); and thickness of the soil layer (cm). The RothC model was run to simulate the turnover of organic carbon in both surface and subsurface soil layers. With its help, scientists discovered different patterns of SOC accumulation. Specifically, the application of manure at sites representing a semi-arid climate was reported cause the SOC content to grow, as seen in India (Bhattacharyya et al., 2013).

Another researcher found SOC accumulation under cover crop and catch crop residues (Autret, 2017). A similar outcome was reported by a meta-analysis (Sulman et al., 2018). A simulation study by Ann E. Russell and B. Mohan Kumar was rather interesting. They found that agricultural systems without trees had a higher carbon storage that did not require spending money on fertilizers or irrigation (Russell and Mohan Kumar, 2019). In an attempt to systematize the body of simulation studies, some authors found that even though the comparison of multiple model structures yielded a wide range of SOC projections, the existing experimental measurements of carbon dioxide fluxes and SOC were not sufficient to either eliminate or validate any of the individual model outcomes. Such uncertainties are justified by the lack of objective information on multiple ways microbes and minerals interact (Sulman et al., 2018). Therefore, more research in these areas is required.

***Problem statement***

Today, it is crucial to provide the world with enough food. This problem requires a comprehensive approach. This study seeks to add to the solution by investigating the carbon cycle and changes in the soil carbon content in irrigated agricultural systems. The goal is to find out how compliance with irrigation norms affects changes in soil carbon concentration. The secondary objective is to assess the potentials and possible limitations of the LPJ-GUESS models used for the said purpose. The present findings can be used for irrigated agriculture planning and in land reclamation projects.

This study aims to determine the impact of irrigation rates on soil carbon dynamics using agricultural system modeling. The objectives of the study are (1) to analyze the latest research on soil carbon dynamics in irrigated agriculture; (2) to identify the most successful methods for increasing soil carbon; (3) to simulate carbon dioxide fluxes in three different biomes; (4) and to compare simulation results with data from other researchers.

**Methods and materials**

This study uses the dynamic ecosystem model (LPJ-GUESS Education 3.0) to simulate the response of agricultural vegetation to changes in air temperature, rainfall, solar radiation, and atmospheric carbon dioxide concentration. The input data for the simulation rounds were read from an environmental driver file, which contains data on climate, CO2 concentration, atmospheric nitrogen deposition, and soil type. The environmental driver file can reflect climate conditions anywhere on Earth.

LPJ-GUESS Education provides researchers with the ability to alter parameters in a manner that fits the purpose of the study. Users can specify the number of simulation years for the static (initialization) and transitional (visible) phases of the simulation in the Simulation protocol field. Note that the static scenario must be at least 500 years. The overall changes to environmental drivers (% or ppm) can also be proposed in the Anomalies field.

Once the parameters are specified, LPJ-GUESS Education generates a text file with simulation data, which is then used to run dynamic simulations of carbon fluxes. This file is the environmental driver file. Before running a simulation, one must decide between the population simulation mode and the cohort simulation mode.

This study seeks to investigate the carbon cycle and carbon accumulation in the soil. Therefore, results from the simulation encompass these processes only. The output folder contains data on carbon balance within the soil, carbon fluxes within the ecosystem, and patterns of plant carbon.

The data analysis process builds on the usage of the analogy method. The variations of carbon in the wild-growing boreal summer grasses were projected onto agricultural crops.

Three irrigated land plots were chosen for the simulation, each located in a different ecosystem. The biomes included in the study were the desert (Republic of Kalmykia), the semi-desert (Republic of Kalmykia) and the steppe (Saratov region).

This study analyzes the experience of more than ten scientific institutions. Among them are education institutions, such as the Kazakh National Agrarian ResearchUniversity, the Auburn University, the Chinese Academy of Sciences, the University of Nebraska-Lincoln, Hainan University, the Swedish University of Agricultural Sciences, and the Arunachal University of Studies. The theoretical framework also includes research by the following organizations: the US Department of Agriculture; the Key Laboratory of Agro-Forestry Environmental Processes and Ecological Regulation of Hainan Province; the Helmholtz Center for Environmental Research (Germany); the Volgograd Branch of the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO); the Kostychev Agrotechnological University (Ryazan); All-Russian Research Institute of Feeds; All-Russian Research Institute of Agricultural Mechanization; Federal Scientific Center of Agroecology, Integrated Land Reclamation and Protective Afforestation; and the Institute of Irrigated Agriculture ( National Academy of Sciences, Ukraine).

Here, the simulation process consisted of a 500-year static phase followed by a 10-year transitional phase. In view of global warming, the following anomalies were proposed: a 1℃ increase in temperature and a 100-ppm increase in atmospheric carbon dioxide concentration. The irrigation norms for each individual area were taken as precipitation anomalies; they distributed equally between the summer months. The irrigation rates were 150 mm (steppe), 500 mm (semi-deserts), and 700 mm (deserts) (Parfenova et al., 2001).

**Results**

The carbon balance of the ecosystem or its components can be either positive or negative, and sometimes carbon neutrality is reported. Carbon positive means that carbon entered the system, and carbon negative means that it has gone. Carbon neutrality refers to an equal balance between the carbon that enters the system and how much is removed from it.

LPJ-GUESS simulated irrigated fields sheltered by native tree species (boreal deciduous trees, temperate broadleaf trees, and evergreen coniferous trees) as well as the boreal summer grass cover. The latter refers to an area of the ground surface covered by herbaceous vegetation native to the temperate regions of the Northern Hemisphere, which grow during the warm season. This study draws an analogy between boreal grasses and crops. Yet, it is worth noting that wild-growing plant species have higher tolerance for changes in environmental drivers compared to cultivars, as well as higher resistance to diseases and pests. The 500-year static phase (initialization) is for the system to reach the state of balance; therefore, it will be ignored. This study analyzes data from the 10-year transition period.

The results of simulation for the desert biome show a slight increase in soil carbon accumulation, from 0.23 to 0.25 kg C/m2/year, likely caused by the soil microorganisms being more active during irrigation. The amount of carbon in the ecosystem carbon exchange first increased by 0.01 kg C/m2/year and then hit a negative value of -0.21 kg C/m2/year as the simulation ended. The likely reason for this dramatic change could be that the carbon accumulated in the soil did not move through the carbon cycle and that the plants in the area were less active under high summer temperatures. The boreal grass cover was found to be carbon positive throughout the entire simulation period, ranging from 0.1 to 0.2 kg C/m2. Finally, the amount of carbon in boreal deciduous trees ranged from 1.3 to 2.2 kg C/m2. In general, the standard irrigation process would be suitable for this biome.

As for the semi-desert biome, the soil carbon accumulation has increased from 0.28 to 0.3 kg C/m2/year. The ecosystem carbon exchange dropped from 0.07 to -0.08 kg C/m2/year. The reasons for this variation are similar to those of the desert biome. The carbon content of the boreal grass cover increased rapidly from 0.1 to 0.2 kg C/m2, and that of the temperate broadleaf tree cover increased slightly in comparison, shifting from 0.001 to 0.02 kg C/m2.

The steppe biome had a positive carbon balance within the soil (0.28 kg C/m2/year), which increased slightly throughout the simulation period, reaching 0.29 kg C/m2/year. The ecosystem carbon exchange decreased from 0.02 to -0.02 kg C/m2/year; the reasons are similar to those of other biomes. Results also show a slight increase in the carbon accumulation rates: from 0.1 to 0.15 kg C/m2, boreal grass cover; from 1.2 to 1.7 kg C/m2, evergreen coniferous tree cover; from 0.7 to 1.0 kg C/m2, temperate deciduous tree cover.

Figure 1 depicts a comparison of soil carbon levels and their dynamics across biomes. As can be seen, there is an upward trend of carbon accumulation. The semi-desert and steppe biomes are very similar in this regard, whereas the desert biome shows the smallest increase in the rate of soil carbon accumulation, which may be due to high summer temperatures affecting the soil-forming microorganisms.

[Figure 1 here]

Figure 2 shows a comparison of ecosystem carbon exchange dynamics. The models simulated a negative shift for all three biomes; the rate of decrease correlated with the stability of the ecosystem. The highest estimates of the ecosystem carbon exchange were simulated for the steppe biome, most likely because this biome has the highest biodiversity among the three. The main argument in support of this assumption is that the desert biome had the lowest ecosystem carbon exchange.

[Figure 2]

Figure 3 shows the dynamic carbon balances of the boreal grass cover. All simulated biomes demonstrated an increase in the carbon balance, but the semi-desert biome stands out with an extremely high increment. Presumably, this biome had the most favorable relationship between environmental drivers.

[Figure 3 here]

The current simulations follow the irrigation norms for agricultural lands. The idea is that these norms ensure a favorable environment for plants and soil-forming microorganisms. To achieve the best environmental and economic results possible, the simulation was based on the lowest permissible norms. The effect turned out to be positive, increasing the soil carbon storage and enhancing the growth of the boreal grass cover.

**Discussion**

It is difficult to compare the results of this study with previous research. The dynamics of the carbon balance reflect the total amount of carbon in the soil without dividing it into inorganic and organic carbon. Yet, only the latter is actively involved in soil fertility formation. The growth of plant biomass may be indicative of an increase in organic carbon content within the soil. Future research can analyze the key drivers behind the simulated increase in the soil carbon content.

The 10-year simulation with specific irrigation rates demonstrated carbon accumulation within the soil and an increase in plant biomass. Similar results were obtained in the Volgograd region, where researchers achieved the arable land productivity of 11.0 to 13.0 units per hectare in the crop-rotation system without using fertilizers (Melikhova et al., 2016). Some other researchers found that soybean grown in the same region can yield 3.0 5 t/ha and 5 t/ha when irrigated using sprinklers and drip irrigation systems, respectively (Borodychev, 2016).

Artificial irrigation was calculated to have a positive effect on the humus condition of soil in the steppe zone of Ukraine. The negative humus balance was observed under non-irrigated conditions and amounted to 0.56 t/ha. Under irrigated conditions, this indicator decreased by 57.1% to 0.24 t/ha. The factors that were taken into account during the calculation process include, but are not limited to, precipitation, irrigation rates, water uptake by plants, soil surface moisture, water movement between soil horizons, and groundwater/surface water interaction (Vozhegova et al., 2016). Treated wastewater can also be used for irrigation, as shown by around 50 countries in the world (Khilchevsky, 2021).

In this study, simulation models do not take artificial fertilization into account; here, the accumulation of soil carbon is due to dead plant decomposition. This method for boosting fertility was reported effective by other researchers. For instance, Baeva found that converting arable lands into the fallow lands initiates the natural succession process, which intensifies the accumulation of organic carbon (Baeva, 2018). The highest concentration of soil carbon was detected in the upper soil layer within the depth of 10 centimeters (Baeva, 2018).

Another study reported the positive impact of perennial grasses on organic carbon content within the soil. The study in point suggested filling organic fertilizers with crop stubble and root residue. A four-year experiment conducted on soddy-podzolic sandy loamy soils under perennial grasses revealed a 0.1% increase in the humus content, mainly in the arable layer. The assumed cause was the presence of root residues in the upper soil layers, which the soil biota converted into organic matter (Gurina et al., 2014). Similar observations were made in Central Chernozem region, the North Caucasus and the Volga region where humus reserves under perennial grasses increased to 0.06 kg/m2 (Trofimova, 2017).

Irrigation and plant decomposition are not the only factors that increase the soil carbon gain; shelterbelts also matter. According the study conducted in the Kamennaya steppe (Voronezh region), shelterbelts reduce the intensity of drought by creating a favorable microclimate (Bobylev, 2005). Other benefits include, but are not limited to, water retention, reduced wind erosion, biodiversity conservation, and higher soil fertility. Another evidence to support the positive impact of shelterbelts on soil fertility in irrigated areas is that the average grain yield near shelterbelts is higher by 34% compared to control plots (Ruleva and Ovechko, 2017).

The results of this study coincide with studies that had similar climatic conditions. The models used here, however, had their limitations: (1) the simulation of the carbon cycle only took into account the interaction of wild vegetation, and (2) the organic and inorganic forms of soil carbon were not examined separately. In addition, the simulation began with the year 1992, with the initialization phase being 500 years, which means that the 10-year period under analysis falls between 2492 and 2502. The simulation algorithms, however, correspond to processes that occur at the present time; therefore, the first limitation can be ignored. If the current climate changes persist at their pace, then in ten years, similar results can be detected in the biomes under consideration, provided that adequate irrigation is provided and that enough stubble and root residues decompose. The shelterbelts should also be kept intact.

**Conclusions**

Results from the LPJ-GUESS simulation are presented for three different biomes: desert, semi-desert and steppe. Carbon accrual rates in semi-desert (0.3 kg C/m2/year) and steppe (0.29 kg C/m2/year) biomes were similar. The desert biome had the smallest carbon gain (0.25 kg C/m2/year). Results also show decrease in the ecosystem carbon exchange for all biomes: desert, -0.21 kg C/m2/year; semi-desert, -0.08 kg C/m2/year; steppe, -0.02 kg C/m2/year. The accumulation rates of carbon for boreal grass cover were found to increase from 0.1 to 0. 2 kg C/m2 in the desert biome and from 0.1 to 0.2 kg C/m2 in the semi-desert biome; for the steppe biome, it increased from 0.1 to 0.15 kg C/m2. Carbon accumulation for boreal deciduous tree cover became higher over the 10-year period, reaching the following values: desert, 2.2 kg C/m2; semi-desert, 0.02 kg C/m2; steppe, 1 kg C/m2. As for the evergreen coniferous cover, the increase in the carbon accumulation rates was as follows: carbon accrual rate of the steppe soil increased from 1.2 to 1.7 kg C/m2. These findings suggest that irrigation rates developed for desert, semi-desert and steppe biomes were effective.

An increase in the SOC content was due to the impact of shelterbelts and dead plant decomposition. The results of this study portray the carbon cycle under the current climate change conditions and thus can be useful in agricultural management and food security projects. The present findings can be applied in irrigated and rainfed agriculture. Specifically, farmers may improve the productivity of irrigated lands in three different ways: through compliance with irrigation norms, by planting shelterbelts to provide water retention and a favorable microclimate, and by converting arable lands to fallow lands to restore fertility.

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**Data availability.** Data will be available on request.

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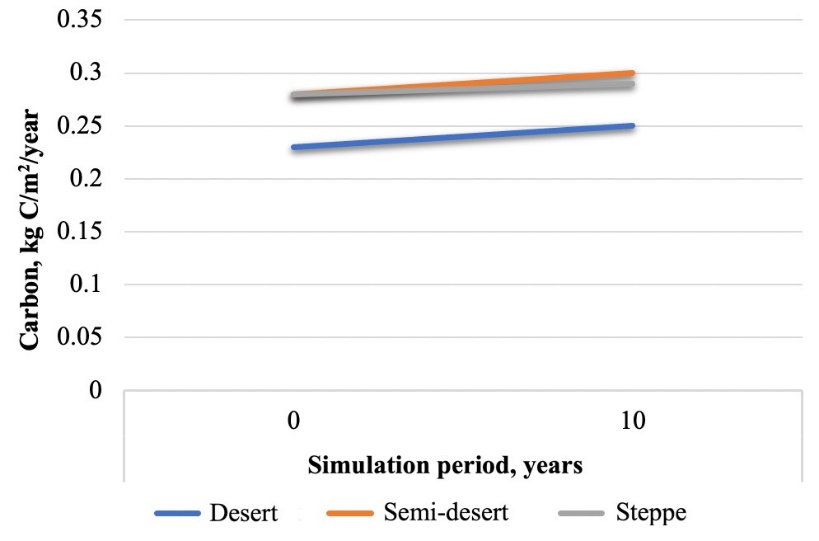
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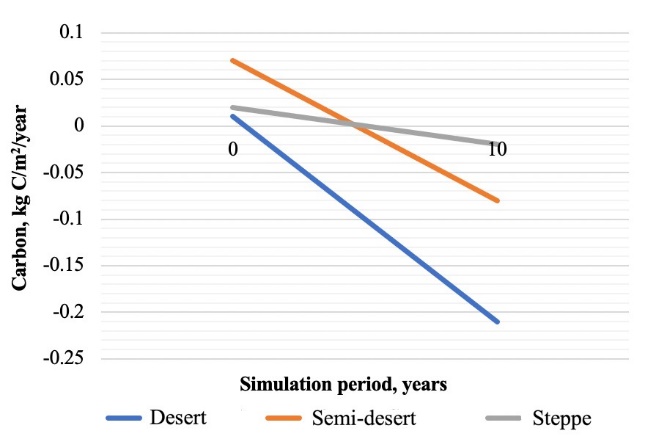
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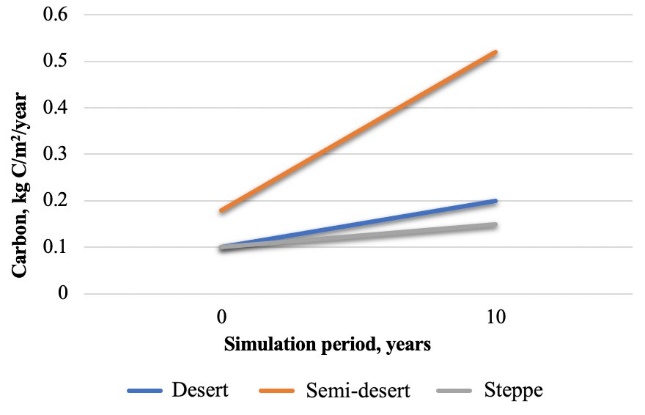
**Figures**

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**Fig. 1:** The carbon balance of agroecosystems and its dynamics over the 10-year period

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**Fig. 2:** Dynamics of the ecosystem carbon exchange over the 10-year period

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**Fig. 3:** The carbon balance of boreal grass covers and its dynamics across different agroecosystems over the 10-year period