COST ESTIMATION AND MODELING OF MACROECONOMIC LOSSES FROM IRRIGATION AND SURFACE SOIL EROSION IN UZBEKISTAN'S AGRICULTURAL SECTOR

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Abstract: *By examining the growing contradictions between rapid population growth in Central Asia and the severe spatial limitations of arable land, this article proposes a scientifically grounded approach to quantifying the costs of soil degradation. The aim of this work is to quantify the direct macroeconomic losses of the agricultural sector based on the internalization of hidden environmental externalities. The economic-mathematical model of economic loss (EL) developed by the authors, by transforming latent qualitative disturbances in the biota into transparent financial indicators, allows for an objective measurement of the "cost of inaction" in the sphere of state land resource management. The study uses official verified data as its information base, according to which 1,772,300 hectares (41.2% of the total arable land area) in the Republic of Uzbekistan are subject to erosion processes, of which 721,900 hectares are affected by the most destructive form of degradation-irrigation-induced degradation. By parameterizing the model using market indicators of grain crop value, the authors demonstrated that the total annual national loss from crop shortfalls reaches \$469.31 million (over 6.1 trillion soums). This result completely refutes outdated departmental methodologies that underestimate the scale of the problem with abstract estimates of "several billion soums.". Summarizing the results of their calculations, the authors propose a strategic reform package that combines targeted biological restoration of arable land, the implementation of end-to-end GIS monitoring based on remote sensing data, and a comprehensive institutional overhaul of long-term land-use rights.*

Keywords: *agricultural economics, soil degradation, irrigation erosion, economic-mathematical modeling, opportunity cost, geographic information systems (GIS), food security, Republic of Uzbekistan.*

INTRODUCTION

One of the central and most complex dilemmas continually facing economic science remains the resolution of the profound contradiction between humanity's virtually limitless needs and the strict spatial limitations of the planet's resources. Within the agricultural sector, this crisis takes on an alarming character, manifesting itself in the progressive erosion and degradation of the soil cover. Soil is a unique, irreplaceable, and practically irrecoverable economic asset on the scale of a human lifetime. In an effort to maximize current short-term profits, modern farms are intensifying land exploitation. Such a strategy, when not supported by adequate investment in land reclamation, inevitably triggers dangerous processes of degumification and the destruction of the arable soil horizon. [1].

Given that the planet's land resources are strictly limited by its geographical boundaries, the potential for the extensive expansion of global arable land can now be considered virtually exhausted. Global demographic dynamics clearly illustrate the scale of this problem. Between 2000 and 2024, the world's population grew rapidly from 6.144 billion to 8.805 billion people; this unprecedented absolute increase of 2.661 billion individuals intensified anthropogenic pressure on the global agrospheric foundation by 43.3%. Under such circumstances, ignoring the ecological degradation of soil revitalizes the classical concept of the 'Malthusian trap.' According to this hypothesis, the rate at which factors of production are destroyed begins to outpace technological breakthroughs in crop yields, thereby putting the very survival of civilization at risk [2].

For the Republic of Uzbekistan, which serves as the main demographic hub of Central Asia, the shortage of high-quality land and water resources is critical. The high share of agricultural production in the structure of national GDP determines the state's strong dependence on the condition of irrigated areas. By using outdated approaches to irrigation and lacking flexible market instruments to assess environmental damage, the sector creates hidden risks that could destabilize the country's economy. This is precisely why the development of a clear, mathematically transparent toolkit for the cost-based internalization of losses has become a top priority for both the academic community and government agencies.

Methods

The main focus of this study is on issues related to soil and its quality; the economic damage caused by soil degradation was also assessed. The following research methods were used in the preparation of this article:

1) The method of observation and data collection-this method involves the systematic monitoring and gathering of necessary facts about an economic entity or phenomenon.

2) The method of deduction-moving from general facts to a specific conclusion [3].

In addition, another methodological foundation is of this study is an interdisciplinary synthesis of systems analysis, mathematical modeling, and statistical clustering methods. With the aim of translating qualitative characteristics of soil degradation into quantitative macroeconomic indicators, the authors adapted a model of aggregate direct financial losses "EL". Unlike abstract estimates, this model is based directly on the areas of land actually affected by specific types of erosion:

$$EL = \sum_{i=1}^{n}(Seri * \Delta Yi * Pi)$$

Where:

S_{eri} - area of land subject to the i - type of erosion (ha)

ΔY_i - standard average yield shortfall of the base indicator crop on eroded land of this type (tons/ha)

P_i - weighted average market value of one ton of agricultural produce (USD/t).

Results

The theoretical foundation for research examining the impact of soil quality on the long-term outcomes of economic activity was laid as early as the works of D. Ricardo and T. Malthus, who provided a detailed justification for the laws of differential rent and diminishing returns in soils. In today's context, these ideas have evolved into the authoritative concept of the "Economics of Land Degradation" (ELD), developed under the auspices of the UN [4].

However, an analysis of the existing body of literature reveals a significant methodological gap. Most domestic studies either limit themselves to a purely agrochemical description of erosion, completely ignoring the financial aspect of the issue, or rely on aggregated departmental estimates based on outdated standards. In such works, the total annual damage is often stated with a vague phrase like "several billion soums per year." This approach, by obscuring the real market value of lost profits, misleads government agencies when allocating budget funds for land reclamation. Thus, there is a clear need to develop a rent-based economic-mathematical model that would be strictly tied to the current structure of the land fund and current prices on global commodity markets [5].

When it comes to the soils of Uzbekistan, the figures are as follows: there are 28 soil types in the country, of which 22 are used more intensively in agriculture, while the remaining 6 are used very rarely. Specifically, light brown meadow-steppe soils cover 578,500 hectares, brown soils – 1,712,800 hectares, dark serozems – 1,208,800 hectares, typical serozems – 2,880,100 hectares, light serozems – 2,191,900 hectares, serozem-meadow and meadow-serozem soils – 1,192,000 hectares, gray-brown and takyr soils – 10,833,900 hectares, gray-brown-meadow soils – 79,200 ha, takyr soils – 1,003,000 ha, takyr-meadow and meadow-takyr soils – 445,600 ha, desert-sandy soils – 2,466,200 ha, meadow and marsh-meadow soils – 3,547,800 ha, typical salt marshes – 793,900 ha, coastal salt marshes – 1,739,600 ha, other lands – 14,159,200 ha. The most fertile are typical and light serozems [6].

We selected food wheat as our benchmark indicator. This choice is fully justified by its strategic role in ensuring the republic's food security, as well as by the availability of transparent price statistics. The study was based on official, verified data. According to this data, the total area of arable land in cultivation is 4,301,700 hectares. Of this, 1,772,300 hectares (or 41.2%) are affected by degradation processes [7]. For the purposes of our calculations, we divided the entire eroded arable land area into two distinct regulatory categories:

1) Land susceptible to irrigation erosion (S_{er1}): This category is officially recorded at 721,900 hectares. As the most destructive form of land degradation, irrigation erosion causes the greatest loss of organic matter and nutrients. Field studies show that yield losses here reach the upper limit - 30% of the baseline level. Assuming an average potential yield of 5.0 t/ha, we have determined the yield loss parameter ΔY_1 to be 1.5 t/ha.

2) Lands subject to other types of erosion (S_{er2}): This group includes areas affected by wind erosion (deflation) and surface water erosion. Their area is calculated as the difference between the total volume of eroded arable land and the area affected by irrigation: 1,772.3 – 721.9 = 1,050.4 thousand ha. = 1 050.4 ha. Crop losses here are taken at the lower limit-20%, which corresponds to a yield shortfall of ΔY_2 amounting to 1.0 t/ha.

The market price per unit of production P has been set at a conservative level of 220$ per ton [8]. This figure represents a reasonable median benchmark between the domestic guaranteed purchase price and the cost of grain imports.

Based on the official data on the degradation of arable land, the authors conducted a step-by-step calculation of the direct financial losses incurred by the agricultural sector of the Republic of Uzbekistan.

Step 1. Calculating the damage caused by irrigation erosion (i = 1):

With its immense destructive power, this type of erosion washes away the most fertile topsoil layer in a single growing season. Applying the model parameters, we obtain:

EL1 = 721,900 ha * 1.5 t/ha * 220 $ = 238,227,000 $

Step 2. Calculating the losses from other types of erosion (i = 2):

Although wind erosion is less aggressive in nature, its widespread spatial distribution results in an equally significant amount of lost revenue:

EL2 = 1,050,400 ha × 1.0 t/ha × 220 $ = 231,088,000 $

Step 3. Aggregating total losses across the arable land base:

By combining the financial results for both categories of damage, we arrive at a comprehensive measure of national losses:

EL_{TOTAL} = 238,227,000 $ + 231,088,000 $ = 469,315,000 $

The final structured simulation results are presented in the calculation table:

Category of soil erosion damage	Actual area (S_{eri}), ha	Percentage of total arable land, %	Yield loss (ΔY_i), t/ha	Total lost production, tons	Market price (P_i), USD/t	Direct economic losses (EL), USD
Irrigation Erosion	721,900	16,80%	1,5	1,082,850	220	238,227,000
Other Types of Erosion	1,050,400	24,40%	1	1,050,400	220	231,088,000
TOTAL:	1,772,300	41,20%	-	2,133,250	-	469,315,000

Precise mathematical calculations clearly demonstrate that the total annual direct economic losses resulting from the erosion of arable land in Uzbekistan amount to $469.31 million. In real terms, due to the deterioration of the soil's basic properties, the agricultural sector loses more than 2.13 million tons of food grain. This is a colossal amount, the shortfall of which seriously limits the state's ability to export products and build up domestic strategic reserves.

Discussion

A comparison of the results obtained with the figures cited in older departmental reports reveals a profound systemic crisis in the methodology for assessing national wealth. As noted earlier, in most local economic studies, the damage caused by erosion is described in vague terms as "several billion soums per year." If we convert the $469.31 million, we obtained into the national currency at the current market exchange rate, the actual damage exceeds 6.1 trillion soums.

Thus, the real macroeconomic "cost of inaction" exceeds outdated expert estimates by nearly a thousand times. Misconceptions about the insignificance of the damage arose because previous methodologies accounted only for the direct costs of surface leveling of fields, completely ignoring the market value of lost profits from reduced crop yields.

Given that nearly every second hectare of arable land in the country (41.2%) is susceptible to erosion, the EL model we propose demonstrates that ignoring environmental externalities leads to a latent devaluation of the republic's agricultural potential. To overcome these negative trends, the authors have developed a reform program in five key areas:

- Biological Agriculture: Widespread incorporation of green manure and cover crops into crop rotations, as well as increased use of organic soil conditioners, which will help restore soil carbon stocks.
- Institutional modernization of lease rights: Granting farmers long-term (up to 49 years) and inheritable land rights, thereby providing them with a direct economic incentive to treat leased plots with care.
- Creation of a Unified GIS Platform: Integration of geographic information systems and Earth Remote Sensing (ERS) data. The use of satellite imagery will enable the rapid identification of new areas of irrigation erosion and the modeling of vegetation index dynamics.
- Development of the ecosystem services market: Creation of a legal framework for generating soil carbon credits, which will open access to foreign ESG investments.
- Introduction of precision agriculture technologies: Transition to differentiated application of mineral fertilizers, which, by reducing excessive chemical loading on serozems, will halt the processes of their accelerated salinization.

Conclusion

Anthropogenic degradation, erosion, and secondary soil salinization trigger a dangerous macroeconomic chain reaction. By destroying soil biodiversity and reducing the natural fertility of arable land, these processes lead to a decline in crop productivity, undermine the forage base for livestock farming, and ultimately threaten the food security of the entire country.

Economic and mathematical modeling has clearly demonstrated that the latent "cost of inaction" amounts to hundreds of millions of dollars in real financial losses annually. Transitioning Uzbekistan's agricultural sector to innovative GIS monitoring and precision farming, along with institutional protection of long-term land users' rights, are fundamental, non-negotiable conditions for ensuring the country's sustainable future.

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