ISSN 2518-7325 (Online), ISSN 2306-1677 (Print)
Land Management, Cadastre and Land Monitoring
Received: 15.08.2026; Accepted: 15.09.2026; Published: 30.09.2026;
http://dx.doi.org/10.31548/zemleustriy2026.03.10

UDC 332.33:631.459:330.131.5

ECONOMIC EFFICIENCY OF INTRODUCTION OF ECOLOGICAL AND TECHNOLOGICAL RESTRICTIONS ON THE USE OF ARABLE LAND IN A TERRITORIAL COMMUNITY

A. Dorosh, *PhD in Economics*

E-mail: andriydorosh@lmi.org.ua

ORCID: 0000-0002-2234-124X

Institute of Land Use of the National Academy of Agrarian Sciences of Ukraine

O. Svyrydov, *PhD student*

E-mail: zemelshik@gmail.com

ORCID: 0009-0002-5433-7795

Institute of Agroecology and Nature Management of the National Academy of Agrarian Sciences of Ukraine

Abstract. *A methodological approach to the quantitative assessment of the economic effect of introducing ecological and technological restrictions on the use of arable land in a territorial community is substantiated. The object of the study is the arable land of the Vinnytsia urban territorial community covering 8,111.8 ha, divided into three ecological and technological groups. The methodology combines pixel-level modelling of soil loss using the Universal Soil Loss Equation, with the topographic factor derived directly from the digital elevation model, the valuation of averted losses through the replacement cost of humus and plant nutrients, and the calculation of net present value across three land-use scenarios. The actual crop structure of 2022 does* *not comply with the norms of optimal crop ratios in rotations: the share of sunflower reaches 43.3-48.0 % against a norm of 5-9 %, while the share of row crops does not decline as erosion hazard increases, peaking at 65.2 % within the second group, where their placement is restricted by law. Modelled soil loss increases from 0.84 to 7.50 t/ha/yr across the groups, and the restrictions level it at 0.51-0.61 t/ha/yr. The net present value over a 20-year horizon ranges from -24.13 to -7.29 million UAH, with a benefit-cost ratio of 0.75-0.95, indicating that averted erosion losses alone cannot recoup the restrictions under flat terrain conditions. The novelty lies in combining digital terrain modelling with cost-benefit analysis and in a three-scenario design separating non-compliance with existing legislation from the intrinsic effect of the ecological and technological division of land.*

Keywords: *land management, land use, economic efficiency, ecological and technological groups, soil erosion, Universal Soil Loss Equation, cost-benefit analysis, field-protective forest belts, territorial community.*

Problem statement. The division of arable land into ecological and technological groups (hereinafter — ETGs) by slope steepness is an established tool of contour-reclamation land organization, grounded in a direct legislative provision: part three of Article 47 of the Law of Ukraine “On Land Protection” prohibits ploughing slopes steeper than 7 degrees and restricts the placement of row crops and bare fallow on slopes of 3 to 7 degrees, while part five of Article 34 provides for determining crops and technologies whose cultivation is restricted [1].

Despite the legal clarity of these requirements, their practical enforcement remains problematic. Land management documentation records ETG boundaries and the corresponding restrictions, yet decisions on crop structure and tillage methods are made by the land user, for whom compliance means an immediate loss of income, while the benefits of preserving soil cover are apparent only in the long term and are only partially capitalized. This is a classic divergence between private and social benefit, which often fails to motivate landowners and land users toward the long-term preservation of land quality. Solving this problem requires not additional prohibitions but a quantitative measurement of the gap between them.

Existing domestic studies focus mainly on the methodological issues of delineating ETGs and on the agronomic justification of soil-protective crop rotations, while the monetary valuation of the consequences of their introduction remains fragmentary. An additional complication is that the conventional methods for calculating losses have lost their legal basis: Resolution of the Cabinet of Ministers of Ukraine No. 1279 of November 17, 1997, on standards for agricultural production losses, has been repealed, and the very concept of compensation for such losses has been removed from the Land Code of Ukraine. This creates a need for methods based on current legal and regulatory acts, present-day agricultural land-use practice, and modern spatial modelling capabilities.

The relevance of the study is reinforced by the fact that most assessments of the effectiveness of anti-erosion measures in Ukraine have been conducted for areas with considerable slope steepness, where the feasibility of protective measures needs no separate justification. For flat communities of the Forest-Steppe, where most arable land lies on slopes of up to 3 degrees, neither the presence nor the absence of an economic effect can be assumed in advance.

Review of recent research and publications. The methodological foundations for dividing arable land into ecological and technological groups were laid down in the work of O.H. Tararyko and M.H. Lobas [2], who substantiated the threshold slope values (3° and 5-7°) as differentiation criteria and the principles for designing crop rotations depending on the ETG. These standards remain the methodological basis for delineating ETG boundaries and designing crop rotations. The structure of grain-grass and grass-arable rotations for second-group land was substantiated by V.F. Saiko and P.I. Boiko [3], while the design of soil-protective and reclamation measures in agrolandscapes, including the placement of forest belts along ETG boundaries, was addressed by S.Yu. Bulyhin, V.I. Burakov and M.M. Kotova [4].

Spatially distributed modelling of erosion-accumulation processes in the agrolandscapes of Ukraine has been developed by O.A. Svetlitchnyi [5], and the assessment of the anti-erosion regulatory capacity of vegetation cover under climate change conditions — by Yu. Nykytiuk and colleagues [6]. Both works confirm the need for quantitative forecasting of erosion rates, yet neither converts physical losses into monetary indicators at the level of an individual community. The international methodological framework is formed by the Universal Soil Loss Equation in its classical [7] and revised [8] versions. The key refinement for spatial application — calculating the slope-length factor from the catchment area — was proposed by P.J.J. Desmet and G. Govers [9], while the relationship between the slope-steepness factor and gradient was refined by D.K. McCool and co-authors [10]. According to the global assessment of rainfall erosivity conducted by P. Panagos and colleagues, the average value of this factor for Ukraine is 422 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$ [11], which is substantially lower than the European average and must be taken into account when parameterizing the model for domestic conditions.

The economic aspects of land management at the community level are examined in the monograph by O.S. Dorosh, I.O.-Yu. Zastulka and A.Y. Dorosh, which calculates the consequences of withdrawing agricultural land from cultivation, accounting for the lost income of landowners, land users and hired workers, as well as local budget revenues [12]. However, this approach relies on standards that are no longer in force and does not include an assessment of averted losses, so it requires updating and refinement. Institutional approaches to planning sustainable land use have been substantiated by O.S. Dorosh [13] and by Y.M. Dorosh, A.V. Barvinskyi and A.Y. Dorosh [14]; the formation of soil-protection restrictions has been addressed by O. Kustovska and O. Polishchuk [15], and the ecological-economic incentive mechanism — in the monograph edited by O.I. Drebot [16]. One of the authors previously proposed an improved methodology for identifying ETGs based on digital elevation models and tested it on the arable land of the Vinnytsia urban territorial community, although the question of the costs and benefits of introducing ETGs remained outside the scope of that publication [17].

A review of the scientific literature reveals two weakly connected strands — the agronomic and land-management justification of ecological and technological restrictions, and the assessment of the economic efficiency of agricultural land use. Accordingly, a methodological apparatus that would allow spatially differentiated physical soil losses to be converted into monetary indicators and compared with the costs of introducing restrictions within a specific community still needs to be developed. To ensure the broadest possible coverage of relevant literature sources, the language model Claude Opus 5 was used for their search and for formatting them according to the DSTU and APA standards.

The aim of the study is to develop and test a methodological approach to the quantitative assessment of the economic efficiency of introducing ecological and technological restrictions on the use of arable land in a territorial community, combining GIS-based spatially distributed modelling of erosion losses with cost-benefit analysis, and allowing the intrinsic effect of the ecological and technological division of land to be separated from the consequences of non-compliance with current crop-rotation legislation.

Materials and methods. The object of the study is the arable land of the Vinnytsia urban territorial community (hereinafter — Vinnytsia UTC), with a total area of 8,111.8 ha, divided into three ecological and technological groups: ETG I (slope 0-3°) covering 7,737.13 ha, subdivided into subgroups Ia (0-1°) — 4,541.96 ha and Ib (1-3°) — 3,195.17 ha; ETG II (3-5°) — 320.64 ha; ETG III (over 5°) — 54.05 ha [17]. The computational part of the model covers 8,030.7 ha, for which relief, soil cover and actual land-use data are simultaneously available.

The information base comprises: a digital elevation model with a resolution of 10 m, constructed from the contour lines of the State Scientific Production Enterprise "Kartographia"; vector layers of ETG boundaries, agro-production soil groups, degree of soil erosion, and agricultural land, based on State Land Cadastre data as of the end of 2021; a raster classification of agricultural crops for 2022 with a resolution of 6.5 m; data from the 10th round of agrochemical survey conducted by the State Institution "Institute for Soil Protection of Ukraine"; and statistical data on crop yields in Vinnytsia oblast and their sale prices as of 2026. Part of the source data was obtained within the authors' previous study [17, 18]. The research was carried out in four stages: spatial modelling of erosion losses, assessment of the actual state of land use, scenario construction, and calculation of economic efficiency indicators.

Annual soil loss was calculated on a pixel-by-pixel basis (10 m resolution) using the Universal Soil Loss Equation [7; 8]:

$$A = R \cdot K \cdot LS \cdot C \cdot P, \qquad (1)$$

where A is the average annual soil loss, t/ha; R is the rainfall erosivity factor, $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$; K is the soil erodibility factor, $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$; LS is the dimensionless topographic factor accounting for slope length and steepness; C is the dimensionless cover-management factor; P is the dimensionless support-practice factor.

A fundamental feature of the approach is the calculation of the topographic factor directly from the digital elevation model, rather than from tabulated values for the natural-agricultural district. The model was pre-processed with hydrological correction, after which flow directions were determined using an eight-direction (D8) scheme and the catchment area of each cell was calculated.

The slope-length component was calculated using the formula proposed by P.J.J. Desmet and G. Govers [9], which operates not on a nominal slope length but on the actual catchment area, making it suitable for complex terrain:

$$L = [(A_{i}\square + D^2)^{(m+1)} - A_{i}\square^{(m+1)}] / [D^{(m+2)} \cdot x^m \cdot 22.13^m], \qquad (2)$$

where $A_{i}\square$ is the contributing catchment area entering the cell, m^2; D is the cell size, m; x is the shape coefficient accounting for slope aspect; $m = \beta / (1 + \beta)$, where $\beta = (\sin\theta / 0.0896) / (3 \cdot \sin^{0.8} \theta + 0.56)$, and θ is the surface slope angle. The catchment area was capped at a value corresponding to a slope length of 300 m, the generally accepted limit of applicability of the equation. The slope-steepness component was calculated using the relationships proposed by D.K. McCool: $S = 10.8 \cdot \sin\theta + 0.03$ for $\tan\theta < 0.09$ and $S = 16.8 \cdot \sin\theta - 0.50$ for $\tan\theta \geq 0.09$ [10].

The rainfall erosivity factor was set at 500 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$: according to the assessment by P. Panagos, the national average for Ukraine is 422, with the steppe and Polissya regions lowering the national average, whereas the Right-Bank Forest-Steppe is better moistened [11].

The soil erodibility factor was set differentially for 24 agro-production soil groups within the study area of the Vinnytsia UTC, ranging from 0.020 to 0.055. For the dominant agro-groups 41d (58.55 % of the area) and 53d (18.92 %), values of 0.032 and 0.030 were adopted, while for eroded varieties (37d, 38d, 49d, 50d) elevated values of 0.040-0.052 were used, reflecting the reduced water stability of soil structure.

The cover-management factor in the baseline scenario was assigned pixel-by-pixel from the raster of actual crop classification, and in the design scenarios — from the composition of the corresponding crop rotations. The support-practice factor was set at 1.00 for tillage without regard to contours, 0.55 for contour tillage in subgroup Ib, and 0.45 in ETG II (Table 1).

Table 1.

Parameters of the spatial soil loss model

Parameter	Adopted value	Basis/source
R, $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$	500	Panagos et al. [11], adjusted for the Right-Bank Forest-Steppe
K: chernozems (41d, 53d, 41v) / dark grey and meadow soils (40d, 45d, 133d)	0.030-0.032/0.033-0.036	Wischmeier — Smith nomograph [7]
K: grey podzolic soils (29v, 29g, 29d, 31v) / eroded varieties (37d, 38d, 49d, 50d)	0.040-0.045/0.040-0.052	Wischmeier — Smith nomograph [7]
LS	calculated from the DEM	Desmet — Govers [9]; McCool et al. [10]
C: sunflower/maize/soybean	0.40/0.35/0.32	Renard et al. [8]
C: winter wheat/rapeseed/perennial grasses	0.12/0.15/0.03	Renard et al. [8]
C: soil-protective rotation (ETG II) / grassing-over (ETG III)	0.09/0.02	Calculated from rotation composition [3, 8]
P: up-and-down slope/contour (Ib) / contour with subsoiling (ETG II)	1.00/0.55/0.45	Renard et al. [8]

Source: compiled by the authors.

The crop classification raster was overlaid on the ETG polygons to calculate the share of each crop within each group, after which the shares were compared with the standards for the optimal crop ratio for the Forest-Steppe region, approved by Resolution of the Cabinet of Ministers of Ukraine No. 164 of February 11, 2010 [19].

Using only two scenarios — “actual state” versus “design state” — would be methodologically incorrect in this study: the actual crop structure violates the current crop-ratio standards, so bringing it into compliance with legislation is an independent requirement, unrelated to the ecological and technological division of land, and attributing the associated costs to the consequences of ETG restrictions would artificially worsen their assessment. A three-scenario modelling approach was therefore applied:

Scenario S_0 — the actual state according to 2022 data: crop structure based on the crop classification raster, tillage without regard to contours, existing forest belts without reconstruction.

Scenario S_1 — compliance with the crop-ratio standards under Resolution No. 164, without differentiation by ETG: winter wheat 30 %, maize 15 %, sunflower 9 %, soybean 8 %, winter rapeseed 4 %, spring cereals 10 %, grain legumes 4 %, perennial grasses 20 %.

Scenario S_2 — standard crop rotations combined with the ecological and technological restrictions previously substantiated by the authors [17]: in subgroup Ib — mandatory contour tillage; in ETG II — a soil-protective grain-grass rotation (perennial grasses 40 %, winter wheat 30 %, spring cereals 20 %, grain legumes 10 %) without row crops or bare fallow; in ETG III — withdrawal from intensive tillage with conservation through grassing-over [20]; allocation of up to 1 % of arable land to new field-protective forest belts.

The effect of compliance with crop-rotation legislation is defined by the difference $S_0 \rightarrow S_1$, and the intrinsic effect of the ecological and technological restrictions — by the difference $S_1 \rightarrow S_2$. The subject of economic evaluation in this study is the second increment; the first is presented for comparison of scale.

The system of field-protective forest belts was planned taking into account their current condition: of the 263.6 ha of recorded linear plantings, 50 % require no intervention, 30 % are suitable for reconstruction, and 20 % require complete replacement. In addition, the establishment of 81.1 ha of new belts is envisaged, of which no more than 9 ha can be placed within ETG III. Accordingly, the area of ETG III designated for conservation through grassing-over amounts to 45.05 ha.

Averted soil losses were valued at replacement cost — the sum of the costs of restoring in the soil the humus and nutrients contained in the averted volume of soil loss. The approach follows the logic of the Methodology approved by Order of the Ministry of Environmental Protection of Ukraine No. 167 of April 4, 2022 [21]:

$$AL = \Delta W \cdot (h \cdot P^h + \Sigma\, n_i \cdot P_i), \quad (3)$$

where AL is the value of averted losses, UAH/yr; ΔW is the averted soil loss, t/yr; h and n_i are the humus content and the content of the i-th available nutrient form, as a share; P^h and P_i are the replacement cost of 1 t of humus and 1 t of active fertilizer substance, UAH.

The humus content was taken at 2.70 %, the content of easily hydrolysable nitrogen (Cornfield method) at 80.0 mg/kg, and the content of available phosphorus and potassium compounds (Chirikov method) at 87.0 and 108.0 mg/kg of soil, respectively, based on the weighted-average data of the 10th round of agrochemical survey of agricultural land [22]. Using available rather than gross forms is essential, since the gross potassium content in chernozems is several times higher and would overstate the valuation. The replacement cost of 1 t of humus was determined through the application of bedded manure at a humification coefficient of 0.05.

Marginal income per hectare was calculated as the difference between the value of gross output and direct production costs:

$$MI = \Sigma\, (Y_i \cdot P_i - C_i) \cdot s_i, \quad (4)$$

where Y_i, P_i, C_i and s_i are the yield (t/ha), sale price (UAH/t), direct production costs (UAH/ha), and the share of the i-th crop in the sown structure.

Yields were adopted as the 2021-2025 average for Vinnytsia oblast [23], and sale prices — from state statistical observation data on the sale of products by agricultural enterprises, at constant 2026 prices [24]. In the absence of current industry-standard technological maps, direct production costs and the additional costs of contour tillage were adopted expertly at 900 UAH/ha per year, based on correction coefficients to output and fuel-consumption norms for field-length class and slope angle [25]. Given this uncertainty, the parameter was tested over a range of 500-1500 UAH/ha in the sensitivity analysis.

The effect of forest belts was assessed as the increase in the value of gross output on the protected area:

$$FB = S\square_{ro}\square \cdot GO \cdot k, \qquad (5)$$

where $S\square_{ro}\square$ is the additionally protected area, ha; GO is the value of gross output per hectare under the standard rotation, UAH/ha; k is the relative yield increase under the protection of forest belts, as a share.

The area ratio was set at 1 ha of forest belt per 25 ha of arable land. This value was determined from the condition of full coverage of the community's arable land by the designed planting system: 344.7 ha of belts provide protection for 8,618 ha against the existing 8,030.7 ha of arable land. The yield increase within the zone of positive influence of field-protective forest belts was set at 5 %. This is the lower bound compared with the literature: Kort's meta-analysis records a consistent yield increase for field and forage crops within the zone of positive influence of field-protective forest belts [26], while Osorio's study, based on production data from onboard yield monitors, reports 10 % for winter wheat and 16 % for soybean [27]. At the same time, the latter study shows that modern varieties and hybrids respond more weakly to protection than older ones, and that compensation for the area removed for planting is not achieved in every configuration, which is why the lower bound of the range was deliberately chosen. The plantings reaching their full protective effect was modelled linearly over ten years from establishment; in the absence of a standard, this period was adopted expertly, based on the time needed for the belt to reach its design height [28].

Net present value over a 20-year horizon, corresponding to two-to-three crop-rotation cycles and the period for forest belts to reach their design height, was chosen as the integral indicator:

$$NPV = \Sigma\ [(AL\square + FB\square) - (\Delta MI\square + LL\square + K\square)] / (1 + r)^{t}, \qquad (6)$$

where $AL\square$ is the value of averted soil losses, UAH; $FB\square$ is the effect of forest belts, UAH; $\Delta MI\square$ is the loss of marginal income due to changes in crop rotation and tillage method, UAH; $LL\square$ is the loss of income from arable land allocated to forest belts, UAH; $K\square$ is capital expenditure, UAH; r is the discount rate; t is the year of the calculation period.

The calculation was performed at three discount rates: 10 % corresponds to the private perspective of the land user (the cost of capital in the agricultural sector), while 5 % and 3 % correspond to the social perspective of the community and are consistent with cost-benefit analysis approaches used in the European Union [29]. In addition, the benefit-cost ratio and payback period were calculated, and the robustness of the results was tested by one-factor sensitivity analysis across five parameters.

The methods used include spatial analysis and geoinformation modelling, monographic and abstract-logical analysis, comparative analysis, scenario modelling, discounted cash flow analysis, and sensitivity analysis. Calculations were performed in the QGIS environment with the GRASS plugin and the Python language. A productive discussion with the language model Claude Opus 5 also took place in the course of developing the methodology.

Results and discussion. Calculating the topographic factor from the digital elevation model produced a result of independent methodological significance: the mean LS values are 0.182 for subgroup Ia, 0.375 for Ib, 0.780 for ETG II, and 1.823 for ETG III, with a weighted average of 0.293 — that is, the gradient is monotonic and nearly tenfold.

This is of fundamental importance: group boundaries are drawn by slope steepness — an indicator that accounts for neither slope length nor flow convergence — whereas the LS factor accounts for both, so the monotonicity of the gradient indicates that the simplified geomorphological criterion is consistent with the result of full-fledged hydrological modelling.

Using the 2022 crop data, the crop classification raster was overlaid on the ETG boundaries. The result revealed a pattern that contradicts not only the recommendations of the previous stage but also the current crop-ratio standards (Table 2).

Table 2.

Actual crop structure of the arable land of the Vinnytsia UTC by ecological and technological group, 2022, % of group area

Crop	**Standard for Forest-Steppe [19]**	**Ia**	**Ib**	**ETG II**	**ETG III**
Sunflower	5-9	44.7	48.0	44.6	43.3
Winter wheat	—	32.0	27.6	24.1	23.9
Maize	—	9.0	11.3	14.9	6.3
Soybean	—	2.1	2.6	5.4	2.2
Winter rapeseed	3-5	2.6	0.9	0.0	0.0
Barley, peas, other	—	0.4	0.5	1.2	3.1
Sugar beet	—	0.4	0.1	0.2	0.0
Perennial grasses, forest, shrubs	10-50	1.9	2.0	3.4	6.8
Unclassified vegetation	—	6.7	6.6	5.5	14.1
Industrial crops, total	5-30	47.7	49.0	44.9	43.3
Row crops, total	**—**	**56.2**	**62.1**	**65.2**	**51.8**

Source: calculated by the authors based on the agricultural crop classification raster and CMU Resolution No. 164 [19].

The share of sunflower exceeds the upper limit of the standard by 4.8-5.3 times and remains virtually unchanged across groups. A note to the standards sets the recurrence of sunflower cultivation at no more frequently than once every seven years, i.e., no more than 12.5 % of the area; the actual 43-48 % implies the crop returning approximately every two years. The share of industrial crops exceeds the standard by 1.4-1.6 times, while perennial grasses account for 1.9-6.8 % against a standard of 10-50 %, and this is an upper-bound estimate, since the corresponding raster class combines grasses with forest and shrubs.

What matters most, however, is not the mere fact of exceeding the standards but the pattern of its spatial distribution: the share of row crops does not decrease as erosion hazard increases but instead rises, peaking at 65.2 % precisely within ETG II, i.e., on slopes of 3-5°, where part three of Article 47 of the Law of Ukraine “On Land Protection” directly restricts their placement. Within ETG III, which is subject to withdrawal from intensive tillage, row crops occupy 51.8 %, while perennial grasses cover only 6.8 % of the area.

Thus, there is no meaningful relationship between land-use intensity and the erosion hazard of the territory: this is not a matter of isolated violations of restrictions but of a systemic absence of land-use differentiation by erosion risk.

Accordingly, spatial modelling of soil loss was carried out for the three scenarios, the results of which are presented in Table 3.

Table 3.

Modelled soil loss on the arable land of the Vinnytsia UTC by scenario

ETG	Area, ha	LS	C (S_0)	Loss S_0, t/ha	Loss S_1, t/ha	Loss S_2, t/ha	Total S_0, thous. t	Total S_1, thous. t	Total S_2, thous. t
Subgroup Ia	4505.5	0.182	0.279	0.84	0.55	0.55	3.78	2.46	2.46
Subgroup Ib	3160.8	0.375	0.294	1.78	1.10	0.61	5.64	3.48	1.92
ETG II	312.1	0.780	0.297	3.79	2.34	0.51	1.18	0.73	0.16
ETG III	52.3	1.823	0.274	7.50	5.24	0.57	0.39	0.27	0.03
Total	**8030.7**	**0.293**	**0.287**	**1.37**	**0.86**	**0.57**	**10.99**	**6.94**	**4.57**

Source: calculated by the authors.

In the actual state, soil loss increases from 0.84 t/ha/yr in subgroup Ia to 7.50 t/ha/yr in ETG III, i.e., nearly ninefold. Compliance with crop-ratio standards reduces it by 37 % across the community but preserves differentiation between groups: in ETG III, soil loss remains at 5.24 t/ha/yr. The introduction of ecological and technological restrictions levels the indicator at 0.51-0.61 t/ha/yr across all groups, i.e., eliminates the dependence of erosion losses on relief. The total volume of soil loss decreases from 10.99 to 6.94 and further to 4.57 thousand t/yr: the $S_0 \rightarrow S_1$ increment yields 4.05 thousand t/yr of averted losses, and the $S_1 \rightarrow S_2$ increment — a further 2.37 thousand t/yr.

For independent verification of the modelling results, the obtained soil-loss values were compared with the actual degree of soil erosion. Within the contours of eroded agro-groups (37d, 38d, 49d, 50d, 55d) covering 77.3 ha, the modelled soil loss averages 3.18 t/ha/yr, with a median of 1.72, whereas on non-eroded soils it is 1.36 and 0.80 t/ha/yr, respectively — i.e., 2.34 times lower. A model built exclusively on relief, soil, and actual land-use data, without calibration against observed erosion, independently reproduced its spatial distribution, confirming the adequacy of the parameterization. The upper 10 % of arable land accounts for 40.3 % of the total volume of soil loss, which justifies the feasibility of targeted rather than blanket measures.

Changing crop rotations — that is, the set of crops and their share of the total area — will inevitably have economic consequences. Calculating the marginal income of crops reveals the economic nature of the problem. At the oblast's average yield [23] and 2026 sale prices [24], sunflower yields about 46 thousand UAH/ha — roughly twice as much as winter wheat, five times more than perennial grasses, and almost a third more than maize. In the absence of current industry-standard technological maps, direct production costs were adopted expertly, so the figures presented should be regarded as estimates; however, the order of magnitude of the ratio is independently confirmed by the actual crop structure, in which the share of sunflower reaches 43-48 % despite the regulatory limit of 5-9 %.

At the same time, sunflower has the highest cover-management factor among the crops grown. The crop most profitable for the land user on a short planning horizon is also the most erosion-hazardous. This is a rational response to the structure of price incentives, which is precisely why an administrative ban without an economic mechanism does not work.

The calculation of marginal income by scenario is presented in Table 4.

Table 4.

Marginal income of the arable land of the Vinnytsia UTC by scenario, UAH/ha per year

ETG	**Area, ha**	**S_0**	**S_1**	**S_2**	**Change $S_0 \rightarrow S_1$**	**Change $S_1 \rightarrow S_2$**
Subgroup Ia	4505.5	35,120	22,759	22,759	-12,361	0
Subgroup Ib	3160.8	36,147	22,759	21,859	-13,388	-900
ETG II	312.1	35,302	22,759	12,920	-12,543	-9,839
ETG III	52.3	34,024	22,759	9,000	-11,265	-13,759
Total, million UAH/yr	**8030.7**	**285.3**	**182.8**	**176.1**	**-102.5**	**-6.6**

Source: calculated by the authors.

This result is key to understanding the structure of the problem: bringing the crop structure into compliance with the standards costs land users 102.5 million UAH of foregone income annually (almost 36 % of its volume), whereas introducing the ecological and technological restrictions themselves, on top of the standard rotation, costs only 6.6 million UAH, or 3.6 %. The main obstacle, therefore, lies not in the ecological and technological division of land but in compliance with general crop-rotation requirements.

However, in addition to the losses, the introduction of ecological and technological restrictions also brings benefits. The components of the $S_1 \rightarrow S_2$ increment effect are as follows. Benefits: averted soil loss of 2,370 t/yr at a replacement cost of 339 UAH/t — 0.80 million UAH/yr; the effect of forest belts on an additionally protected area of 4,655 ha, at a gross output value of 51,979 UAH/ha and a 5 % yield increase — 12.10 million UAH/yr. Annual costs: loss of marginal income — 6.64 million UAH; loss of income from 81.1 ha of arable land allocated to new forest belts — 1.85 million UAH. Capital expenditure: new forest belts with land-management projects — 11.76 million UAH; reconstruction and replacement of existing plantings — 11.07 million UAH; conservation of 45.05 ha of ETG III through grassing-over [20] — 1.94 million UAH; totaling 24.77 million UAH as a one-time expense.

Comparing these components produces the first substantive result: the value of averted soil losses is 0.80 million UAH per year, whereas the annual costs of introducing the restrictions amount to 8.49 million UAH, i.e., a ratio of approximately 1:10.6. This means that the anti-erosion effect alone cannot recoup the introduction of ecological and technological restrictions under the flat-relief conditions of the Vinnytsia UTC. The reason is evident from Table 3: the average modelled soil loss in the actual state is 1.37 t/ha/yr, which is below the permissible erosion norms for chernozems accepted in domestic practice, and the excess is localized only within ETG II and III — on 364.4 ha, or 4.5 % of the arable land area.

The main benefit is formed by the forest-reclamation component — 12.10 million UAH per year, which is fifteen times greater than the anti-erosion effect: forest belts act not by preventing soil loss but by altering the microclimate of the protected area, and this mechanism is more significant under flat-relief conditions. In the absence of current cost-estimate standards, the cost parameters of forest-reclamation measures, humus restoration, and conservation were adopted expertly. The key ones were tested in the sensitivity analysis.

The results of discounted cash flow analysis over a 20-year horizon are presented in Table 5.

Table 5.

Indicators of the economic efficiency of introducing ecological and technological restrictions

Indicator	**r = 3 % (social perspective)**	**r = 5 % (social perspective)**	**r = 10 % (private perspective)**
Discounted benefits, million UAH	143.0	115.0	70.6
Discounted costs, million UAH	150.3	129.3	94.8
Net present value, million UAH	-7.29	-14.33	-24.13
Benefit-cost ratio	0.95	0.89	0.75
Discounted break-even period, years	24	32	not reached

Source: calculated by the authors.

Net present value is negative at all discount rates, though the nature of the negativity differs: at the social rate of 3 %, the benefit-cost ratio is 0.95, i.e., implementation of all modelled measures is close to break-even, whereas at the private rate of 10 % it drops to 0.75. The gap between private and social benefit amounts to 16.8 million UAH in present value — a quantitative expression of the compensation required for landowners and land users. The distribution of the effect over time is also telling: the modelled measures reach a stable positive annual balance (+4.42 million UAH) as early as the tenth year, yet the undiscounted payback period is 18 years, and at the social rate of 5 %, discounted break-even is reached only in year 32. Implementing these restrictions and measures does pay off, but beyond the modelling horizon.

The study also included a one-factor sensitivity analysis of the model, the results of which are presented in Table 6.

The analysis reveals a sharply asymmetric structure of uncertainty: the range of the result with respect to the yield increase within the zone of positive influence of field-protective forest belts (146.98 million UAH) is more than three times greater than the range for any other parameter, and at a 10 % increase, consistent with estimates common in the literature, net present value reaches +90.65 million UAH. The result is therefore determined primarily by the forest-reclamation component, and the 5 % increase adopted in the baseline calculation is the lower bound of the literature range, which makes the negative baseline result deliberately conservative.

Table 6.

Sensitivity analysis of net present value (r = 5 %), million UAH

Parameter	Test range	Lower value	Base value	Upper value	Range
Yield increase under forest-belt protection	3-10 %	-56.33	-14.33	+90.65	146.98
Additional costs of contour tillage	500-1500 UAH/ha	+2.98	-14.33	-40.30	43.28
Discount rate	3-10 %	-7.29	-14.33	-24.13	16.83
Cost of establishing 1 ha of forest belt	90-160 thous. UAH	-10.51	-14.33	-19.43	8.92
Replacement cost of 1 t of soil	250-500 UAH/t	-16.97	-14.33	-9.59	7.38

Source: calculated by the authors.

The second most influential parameter is the additional cost of contour tillage, which is explained by the large area of subgroup Ib — 3,160.8 ha; at the lower value of 500 UAH/ha, net present value becomes positive. The weakest influence is exerted by the replacement cost of soil — precisely the parameter through which the anti-erosion effect is valued: even when it is doubled, the modelled measures remain loss-making, which conclusively confirms the secondary importance of this component under flat-relief conditions.

The findings of the study are entirely valid, yet three caveats deserve mention. Data on crop structure relate to 2022 and represent a single-year snapshot rather than an observation over a full rotation cycle; at the same time, sunflower sown areas in

Ukraine that year were lower than pre-war levels, which gives grounds to consider the identified structure rather typical. The “unclassified vegetation” class (5.5-14.1 % of the area) was included in the calculation with an averaged cover factor. The impact of climate change was not accounted for, and as the intensity of heavy rainfall increases, the anti-erosion component will grow, which will raise the economic feasibility of introducing the modelled measures.

Conclusions and proposals. A methodological approach has been developed and tested for the quantitative assessment of the economic efficiency of introducing ecological and technological restrictions on the use of arable land in a territorial community, combining spatially distributed modelling of erosion losses using the Universal Soil Loss Equation with cost-benefit analysis. A key methodological feature is the calculation of the topographic factor directly from the digital elevation model created at the stage of forming the ecological and technological groups, which ensures that the calculation is tied to a specific territory and maintains continuity between the stages of the research.

The use of a three-scenario modelling approach has been substantiated, separating the consequences of non-compliance with current crop-ratio standards in rotations from the intrinsic effect of introducing ecological and technological restrictions on the use of arable land. The need for such a separation is confirmed quantitatively: bringing the crop structure into compliance with the standards costs land users 102.5 million UAH of foregone marginal income annually, whereas introducing the ecological and technological restrictions on top of the standard rotation costs only 6.6 million UAH — an amount that, had only two scenarios been modelled, would have been erroneously attributed to these restrictions.

It has been established that the actual use of the community's arable land is not differentiated by erosion hazard: the share of sunflower is 43.3-48.0 % against a standard of 5-9 %, and the share of row crops reaches a maximum of 65.2 % precisely within ETG II, where their placement is restricted by law. The model has passed independent validation: on the contours of actually eroded soils, the modelled indicator is 2.34 times higher, and the upper 10 % of arable land accounts for 40.3 % of soil losses, which justifies the feasibility of targeted measures.

The LS factor, calculated from the digital elevation model, increases monotonically from 0.182 in subgroup Ia to 1.823 in ETG III, providing independent confirmation of the consistency between the boundaries of the ecological and technological groups and the result of hydrological modelling. Introducing the restrictions reduces average soil loss from 0.86 to 0.57 t/ha/yr and levels it at 0.51-0.61 t/ha/yr across all groups. Net present value over the 20-year horizon amounts to -7.29 million UAH at a 3 % rate, -14.33 million UAH at a 5 % rate, and -24.13 million UAH at a 10 % rate, with benefit-cost ratios of 0.95, 0.89, and 0.75, respectively.

The main substance of the result is that in flat Forest-Steppe communities, where average soil loss does not exceed permissible norms and the excess is localized on less than 5 % of arable land, the anti-erosion component alone cannot recoup the introduction of restrictions: the value of averted soil losses is more than ten times smaller than the annual costs. The forest-reclamation component is decisive, its effect being fifteen times greater. Consequently, the economic justification of restrictions for such territories should be built primarily on the forest-reclamation and long-term productivity effects rather than on the reduction of soil loss.

The gap between private and social benefit amounts to 16.8 million UAH in present value and explains why the restrictions are not introduced voluntarily: the land user assesses the measure as loss-making by more than a fifth, whereas for the community it is practically break-even. A further important argument is that the payback period is 18 years, and at the social rate of 5 %, discounted break-even is reached only in year 32. Implementing these restrictions and measures does pay off, but beyond the modelling horizon. In light of this, it is proposed: to establish ecological and technological restrictions as material terms of agricultural land lease agreements, with corresponding adjustment of rent; to treat the identified gap between private and social valuation as a substantiated upper limit for compensation payments within the economic incentive mechanisms provided for by Article 205 of the Land Code of Ukraine; and to give priority to forest-reclamation measures, as the component with the highest return, when developing programmes for the use and protection of community land.

Prospects for further research are related to refining the additional costs of contour tillage based on technological maps, since this parameter determines the sign of the result, as well as to extending the time series of crop-structure data and incorporating a carbon component into the modelling.

References

1. Pro okhoronu zemel [On land protection]: Zakon Ukrainy vid 19.06.2003 No. 962-IV [Law of Ukraine No. 962-IV of June 19, 2003]. Available at: https://zakon.rada.gov.ua/laws/show/962-15

2. Tararyko, O. H., & Lobas, M. H. (1998). Normatyvy gruntozakhysnykh konturно-melioratyvnykh system zemlerobstva [Standards for soil-protective contour-meliorative farming systems]. Kyiv: Ahroinkom. 158.

3. Saiko, V. F., & Boiko, P. I. (2002). Sivozminy u zemlerobstvi Ukrainy [Crop rotations in Ukrainian agriculture]. Kyiv: Ahrarna nauka. 148.

4. Bulyhin, S. Yu., Burakov, V. I., & Kotova, M. M. (2004). Proektuvannia gruntozakhysnykh ta melioratyvnykh zakhodiv v ahrolandshaftakh [Design of soil-protective and reclamation measures in agrolandscapes]. Kyiv: NAU. 114.

5. Svetlitchnyi, A. A. (2009). Soil erosion induced degradation of agrolandscapes in Ukraine: Modeling, computation and prediction in conditions of the climate changes. In P. Y. Groisman & S. V. Ivanov (Eds.), Regional aspects of climate-terrestrial-hydrologic interactions in non-boreal Eastern Europe (pp. 187–194). Dordrecht: Springer. DOI: https://doi.org/10.1007/978-90-481-2283-7_21

6. Nykytiuk, Y., Kravchenko, O., Pitsil, A., Bambura, V., & Seredniak, D. (2025). Global climate change may reduce the anti-erosion regulatory capacity of vegetation cover in Ukraine’s Polissya and Forest-Steppe regions. Regulatory Mechanisms in Biosystems, 16(1), Article e25004. DOI: https://doi.org/10.15421/0225004

7. Wischmeier, W. H., & Smith, D. D. (1978). Predicting rainfall erosion losses: A guide to conservation planning. Washington, DC: USDA. (Agriculture Handbook No. 537).

8. Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., & Yoder, D. C. (1997). Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Washington, DC: USDA. (Agriculture Handbook No. 703).

9. Desmet, P. J. J., & Govers, G. (1996). A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. Journal of Soil and Water Conservation, 51(5), 427–433.

10. McCool, D. K., Brown, L. C., Foster, G. R., Mutchler, C. K., & Meyer, L. D. (1987). Revised slope steepness factor for the Universal Soil Loss Equation. Transactions of the ASAE, 30(5), 1387–1396.

11. Panagos, P., Borrelli, P., Meusburger, K., et al. (2017). Global rainfall erosivity assessment based on high-temporal resolution rainfall records. Scientific Reports, 7, Article 4175. DOI: https://doi.org/10.1038/s41598-017-04282-8

12. Dorosh, O. S., Zastulka, I. O.-Yu., & Dorosh, A. Y. (2024). Ekoloho-ekonomichnyi rozvytok terytorialnykh hromad ta yoho parametralne zabezpechennia [Ecological and economic development of territorial communities and its parametric support]. Kyiv: FOP Huliaieva V. M.

13. Dorosh, O. S., Dorosh, A. Y., Saliuta, V. A., & Melnyk, D. M. (2022). Instytutsiini pidkhody do planuvannia staloho vykorystannia ta okhorony silskohospodarskykh zemel na terytorii okremykh zemlekorystuvan [Institutional approaches to planning sustainable use and protection of agricultural land within individual land uses]. Zemleustrii, kadastr i monitorynh zemel, (4), 16–26. DOI: https://doi.org/10.31548/zemleustriy2022.04.02

14. Dorosh, Y. M., Barvinskyi, A. V., & Dorosh, A. Y. (2022). Kontseptualni zasady formuvannia systemy ratsionalnoho silskohospodarskoho zemlekorystuvannia [Conceptual principles of forming a system of rational agricultural land use].

Zemleustrii, kadastr i monitorynh zemel, (1), 45–56. DOI: https://doi.org/10.31548/zemleustriy2022.01.05

15. Kustovska, O., & Polishchuk, O. (2019). Do pytannia formuvannia gruntookhoronnykh obmezhen pry vykorystanni zemel silskohospodarskoho pryznachennia [On the formation of soil-protective restrictions in the use of agricultural land]. Zemleustrii, kadastr i monitorynh zemel, 25(4), 92–97. DOI: https://doi.org/10.31548/zemleustriy2019.04.10

16. Drebot, O. I., Vysochanska, M. Ya., & Komarova, N. V. (Eds.). (2021). Instytutsionalne zabezpechennia zbalansovanoho vykorystannia ta okhorony zemel silskohospodarskoho pryznachennia [Institutional support for balanced use and protection of agricultural land]. Kyiv: Ahrarna nauka. 280.

17. Dorosh, Y., Dorosh, O., Barvinskyi, A., Dorosh, A., & Kolisnyk, H. (2022). GIS tools in the formation of environmentally friendly use of agricultural landscapes. In International Conference of Young Professionals "GeoTerrace-2022": Conference proceedings (pp. 1–5). European Association of Geoscientists & Engineers. DOI: https://doi.org/10.3997/2214-4609.2022590026

18. Ibatullin, Sh., Dorosh, Y., Sakal, O., Dorosh, O., & Dorosh, A. (2022). Crop identification using remote sensing methods and artificial intelligence. In International Conference of Young Professionals "GeoTerrace-2022": Conference proceedings (pp. 1–5). European Association of Geoscientists & Engineers. DOI: https://doi.org/10.3997/2214-4609.2022590016

19. Pro zatverdzhennia normatyviv optymalnoho spivvidnoshennia kultur u sivozminakh v riznykh pryrodno-silskohospodarskykh rehionakh [On approval of standards for the optimal ratio of crops in crop rotations in different natural-agricultural regions]: Postanova Kabinetu Ministriv Ukrainy vid 11.02.2010 No. 164 [Resolution of the Cabinet of Ministers of Ukraine No. 164 of February 11, 2010]. Available at: https://zakon.rada.gov.ua/laws/show/164-2010-п

20. Pro zatverdzhennia Poriadku konservatsii zemel [On approval of the Procedure for land conservation]: Postanova Kabinetu Ministriv Ukrainy vid

19.01.2022 No. 35 [Resolution of the Cabinet of Ministers of Ukraine No. 35 of January 19, 2022]. Available at: https://zakon.rada.gov.ua/laws/show/35-2022-п

21. Pro zatverdzhennia Metodyky vyznachennia rozmiru shkody, zavdanoi zemli, gruntam vnaslidok nadzvychainykh sytuatsii ta/abo zbroinoi ahresii ta boiovykh dii pid chas dii voiennoho stanu [On approval of the Methodology for determining the amount of damage caused to land and soils as a result of emergencies and/or armed aggression and hostilities during martial law]: Nakaz Ministerstva zakhystu dovkillia ta pryrodnykh resursiv Ukrainy vid 04.04.2022 No. 167 [Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 167 of April 4, 2022]. Available at: https://zakon.rada.gov.ua/laws/show/z0406-22

22. Yatsuk, I. P. (Ed.). (2018). Naukovi doslidzhennia z monitorynhu ta obstezhennia silskohospodarskykh uhid Ukrainy za rezultatamy Kh tury (2011–2015 rr.) [Scientific research on monitoring and surveying agricultural lands of Ukraine based on the results of the 10th round (2011–2015)]. Kyiv: DU “Instytut okhorony gruntiv Ukrainy.” Available at: http://www.iogu.gov.ua/wp-content/uploads/2013/07/Monitorynh-20171.pdf

23. Derzhavna sluzhba statystyky Ukrainy. (n.d.). Ploshchi, valovi zbyry ta urozhainist silskohospodarskykh kultur za yikh vydamy ta po rehionakh: Derzhavne statystychne sposterezhennia [Areas, gross harvests and yields of agricultural crops by type and region: State statistical observation]. Available at: https://ukrstat.gov.ua/operativ/operativ2022/sg/pvzu/arch_pvxu_reg.htm

24. Derzhavna sluzhba statystyky Ukrainy. (n.d.). Realizatsiia produktsii silskohospodarskymy pidpryiemstvamy: Statystychna informatsiia [Sales of agricultural products by agricultural enterprises: Statistical information]. Available at: https://ukrstat.gov.ua/druk/publicat/kat_u/publ7_u.htm

25. Demchak, I. M., Pyvovar, V. S., Ivchenko, V. M., Kuksa, L. V., et al. (2019). Metodychni polozhennia ta normy produktyvnosti i vytrat palyva na zbyranni silskohospodarskykh kultur [Methodological provisions and standards of productivity and fuel consumption for harvesting agricultural crops]. Kyiv: NDI “Ukrahropromproduktyvnist”. 160.

26. Kort, J. (1988). Benefits of windbreaks to field and forage crops. Agriculture, Ecosystems & Environment, 22–23, 165–190. DOI: https://doi.org/10.1016/0167-8809(88)90017-5

27. Osorio, R. J., Barden, C. J., & Ciampitti, I. A. (2019). GIS approach to estimate windbreak crop yield effects in Kansas–Nebraska. Agroforestry Systems, 93(4), 1567–1576. DOI: https://doi.org/10.1007/s10457-018-0270-2

28. Brandle, J. R., Hodges, L., & Zhou, X. H. (2004). Windbreaks in North American agricultural systems. Agroforestry Systems, 61, 65–78. DOI: https://doi.org/10.1023/B:AGFO.0000028990.31801.62

29. European Commission, Directorate-General for Regional and Urban Policy. (2015). Guide to cost-benefit analysis of investment projects: Economic appraisal tool for Cohesion Policy 2014–2020. Luxembourg: Publications Office of the European Union. 358.

А.Й. Дорош, О.М. Свиридов

ЕКОНОМІЧНА ЕФЕКТИВНІСТЬ ЗАПРОВАДЖЕННЯ ЕКОЛОГО-ТЕХНОЛОГІЧНИХ ОБМЕЖЕНЬ У ВИКОРИСТАННІ ОРНИХ ЗЕМЕЛЬ ТЕРИТОРІАЛЬНОЇ ГРОМАДИ

Анотація. *Обґрунтовано методичний підхід до визначення економічного ефекту від запровадження еколого-технологічних обмежень у використанні орних земель територіальної громади. Об'єктом дослідження є орні землі Вінницької міської територіальної громади площею 8111,8 га, поділені на три еколого-технологічні групи. Методологія поєднує попіксельне моделювання змиву ґрунту за універсальним рівнянням втрат ґрунту, у якому рельєфний фактор обчислено безпосередньо з цифрової моделі рельєфу, оцінку відвернених втрат за відновною вартістю гумусу й поживних речовин та розрахунок чистої приведеної вартості за трьома сценаріями землекористування. Встановлено, що фактична структура посівів 2022 року не відповідає нормативам оптимального співвідношення культур у сівозмінах: частка соняшнику становить 43,3-48,0 % за нормативу 5-9 %, а частка просапних культур не* *знижується з наростанням ерозійної небезпеки, сягаючи максимуму 65,2 % у межах другої еколого-технологічної групи, де їх розміщення обмежене законом. Модельований змив ґрунту зростає від 0,84 т/га/рік у підгрупі Іа до 7,50 т/га/рік у третій групі, а запровадження обмежень вирівнює його на рівні 0,51-0,61 т/га/рік. Чиста приведена вартість за горизонтом 20 років становить від -24,13 млн грн за ставки дисконтування 10 % до -7,29 млн грн за ставки 3 % при індексі зисків і витрат 0,75-0,95, що свідчить про неспроможність ерозійних втрат, яким удалося запобігти, самостійно окупити запровадження обмежень в умовах рівнинного рельєфу. Наукова новизна полягає в поєднанні цифрового моделювання рельєфу з аналізом витрат і зисків та в обґрунтуванні використання підходу з моделюванням трьох сценаріїв, який відокремлює наслідки недотримання чинного законодавства від ефективності підходу поділу орних земель за еколого-технологічними групами.*

Ключові слова: *землеустрій, землекористування, економічна ефективність, еколого-технологічні групи, ерозія ґрунтів, універсальне рівняння втрат ґрунту, аналіз витрат і зисків, полезахисні лісові смуги, територіальна громада.*