Mathematical Modeling of Environmental Degradation Based on Control Science

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Abstract: In terms of the cost of environmental degradation based on Control Science, we divide it into five parts: water pollution, declining air quality, reduced vegetation coverage, land resource loss, and declining biodiversity. To establish the ecological service evaluation model, we choose different sub-models to evaluate diverse factors effectively. Additionally, these factors will undoubtedly affect each other, which means that comprehensive environmental degradation costs should be obtained through multi-factors analysis.

1. Introduction

With the development of modern society, in order to meet the needs of different people, construction projects are becoming more and more intense, while these construction projects will undoubtedly have a certain impact on the natural environment. However, modern economic theories tend to neglect its impact on the global biosphere, regarding the biosphere as a system with unlimited production capacity. The biosphere provides various kinds of natural processes to sustain the health of the environment, which is called ecosystem services. For example, our biosphere owns the ability to degrade garbage, pollinate plants, circulate carbon and oxygen, and so on. However, when human beings make use of the ecosystems to construct some projects, we may limit even destroy the functions of ecosystems [1].

2. Models for the Environmental impact factors

We divide the aspects of environmental degradation into five categories: water pollution, air pollution, land pollution, vegetation coverage reduction, as well as biodiversity decline.

The environmental costs are estimated based on certain indicators corresponding to these five categories. Among them, we use the INVEST model for water pollution and land pollution analysis. At the same time, the CITY-green model is used to evaluate air pollution and vegetation coverage, the LCM model is accustomed to estimate the biodiversity decline. More importantly, a PAC-based PCA (principal component analysis) is accustomed to comprehensively evaluate the overall model and come up with the environmental degradation cost estimate.

3. CITY-green Model

3.1 Air quality reduction cost estimation

3.1.1 Carbon storage and carbon absorption

Plants are irreplaceable for maintaining the atmospheric balance. Green plants can absorb carbon dioxide (CO_2) in the air through their own photosynthesis, producing organic matter and releasing oxygen (O_2) to ensure the balance of the ecosystem. Carbon dioxide is one of the main greenhouse gases, while green plants play a pivotal role in reducing carbon dioxide. Through the carbon stored in the forest before and after the construction of the project, we can assess the transformation of carbon dioxide. The CITY-green model classifies the age of trees into four types: young, middle, mature, and overripe [1].

Calculation formula for carbon storage:

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$$C_V = A_R * G_C * C_F$$

The C_V is the carbon storage (t), A_R is the area of the area (hm^2), G_C is the forest coverage (%), C_F is the carbon storage factor.

The carbon tax method is used for calculating the value of carbon storage and carbon absorption. With the purpose of reducing greenhouse gases emissions, many countries have established a tax collection system for carbon dioxide.[5] Carbon storage and carbon absorption ecological benefits are defined as the "shadow price". The related formula is as follows:

$$V_1 = M \times T_1$$

V_1 is the annual economic value of forest carbon storage in carbon absorption, M is the carbon storage and carbon absorption amount, and T_1 is the carbon tax rate.

3.1.2 Removal of atmospheric pollutants

The CITY-green model has available to calculate the ecological benefits of sulfur dioxide, ozone, respirable particulate matter, nitrogen dioxide, and carbon monoxide, which are included in the ecological cost. Forest vegetation does well in breaking down, absorbing, as well as fixing air hazards, but if they are artificially chemically treated, it will add some extra cost to purify the air. It is acknowledged that the amount of air pollution absorbed by trees is closely related to the deposition rate of pollution and the concentration of atmospheric pollutants. The CITY-green model is based on the UFORE model, to calculate the amount of air pollution absorbed by trees [2].

The calculation formula is as follows:

$$F_1 = \text{Vd} \times \text{C}$$

F_1 is the purification rate of the pollutant $(\text{g} \cdot cm^{-2} \cdot sec^{-1})$

Vd is the deposition rate$(\text{cm} \cdot sec^{-1})$

Trees owe natural abilities to purify air's harmful pollutants. With the trees' deficiency, the ecosystem will be further destroyed, harmful substances in the air will cause further damage to the ecological balance, thus forming a vicious circle. In conclusion, when the ecosystem is unable to naturally modulate harmful substances in the air, it requires manual processing, resulting in additional environmental degradation costs. The formula is as follows:

$$\text{U} = F_1 \times \text{u}$$

U is the total cost, u is the average cost

The air quality city can affect the removal of atmospheric pollutants. Because it is unable to modify the parameter values, we use default in the software, set S to 4.65 °and, Precipitation is set to 5.12in.

3.2 Forest Coverage Reduction Results Assessment

The basic cost of Maintaining the soil and water conservation

The cost of decreasing urban forest cover mainly aims to maintain the soil and water conservation. For instance, urban forests help reduce both storm runoff and the payment of flood control facility construction. What's more, for the reason that trees have access to intercept water, which affects the spatial distribution of hydrology and humidity, they are the vehicle for reducing the cost of soil and water conservation infrastructure. The CITY-green model calculates the stormwater runoff based on the TR-55 hydrological model of the US Soil and Water Conservation Department, which is related to the terrain slope, rainfall distribution, soil type, etc.

The calculation formula is as follows:

$$\text{S} = \left(\frac{1000}{\text{CN}}\right) - 10$$

$$\text{Vr} = \text{Q} \times \text{E}$$

$$Q = \left[\frac{(P-0.2S)^2}{P}\right] + 0.8 \times S$$

V_r is the annual runoff, E is the total area of the study area, P is the rainfall of the area, S is the slope value, CN is the soil curvature value of the during rainfall.

When calculating the environmental degradation cost of forest reduction, the market substitution method can be adopted. The other adjusted investment amount is used as the “substitution price” to calculate the environmental degradation cost. The formula is as follows:

$$V_2 = R_1 \times P_2$$

V_2 is forest regulation Annual economic value, R_1 is the total amount of forest regulation, and P_2 is the cost of the forest

4. LCM Model

The Land Change Modeler (LCM) model is a classic method for species habitat suitability and biodiversity analysis.[8] The model not only provides with traditional biodiversity-based analytical tools, but also uses spatial multi-scales, combing with habitat assessments, to provide a quantitative basis for biodiversity change.

Based on the multiple environment variables, the LCM model will calculate the Mahalanobis distance according to the Mahalanobis Typicality calculation principle. Even the so-called typical probability value (Typicality probability, environmental variable minus). The X^2degree of freedom test of 1 has a value of 0 and 1, and the magnitude of the value represents each grid.

$$D = \sqrt{(x-u_i)^T V_i^{-1} (x-u_i)}$$

D is the requested Mahalanobis distance, x is the I environment variable parameter value of the grid x, $u_i$is the parameter average of the I environment variables of all the grids, V_i is the land utilization of the x grid. The transfer matrix of the type matrix, T is the number of transitions of the transfer matrix. [3]

Through the change of the number of grids, the area ratio in a proportion of sub-habitats, the main potential ecological corridors, sub-potential ecological corridors can be obtained. In conclusion, the formula for the cost of maintaining biodiversity can be obtained:

$$F_2 = \alpha \times S^D$$

F_2 is the cost of ecological habitat maintenance, α is the cost of ecological habitat maintenance per unit area, S^D is total habitat area (grid number multiplied by size)?

5. InVEST Model

InVEST model（The Integrate Valuation of Ecosystem Services and Tradeoffs Tool）is an eco-pneumatic service function assessment tool jointly developed by Stanford University, the World Wide Fund for Nature and the Nature Conservancy[4].

5.1 Land loss maintenance cost

In this paper, the soil conservation model in InVEST is used to evaluate the soil conservation ability around the project.[10] The formula is as follows:

$$R = E_1 \times I_{30}$$

$$K = \frac{\left[2.1 \times 10^{-4}(12-O)M^{1.14} + 3.25 \times (S-2) + 2.5 \times \left(P_J - 3\right)\right]}{100} \times 0.1317\#$$

$$C = 0.988 \times e^{-0.11Rv}$$

$$\beta = R \times K \times LS \times C \times P$$

R is the rainfall erosion capacity, E_1 is the rainfall kinetic energy, I_{30} is the maximum rainfall intensity within 30 minutes, C is the vegetation cover and management factor of the waste grassland, Rv is the vegetation coverage, K is the soil erodibility, and LS is the average slope. P is the engineering measure factor (take different values according to the scale of the project) β is the land loss degree:

$$F = \beta \times d \times S$$

F is the cost of land maintenance, d is the cost of land maintenance land per unit area, S is the land area.

5.2 Water management costs

Water production module in InVEST model is a kind of estimation method based on water balance. In the model, the grid unit minus the actual rainfall evaporation of water is the water supply, including the surface runoff, soil water content, the canopy entrapment volume, etc.

The formulas are as follows:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x$$

$$\frac{\mathrm{AE}T_{xj}}{P_x} = \frac{1 + w_x R_{xj}}{1 + w_x R_{xj} + \frac{1}{R_{xj}}}$$

$$w_x = Z \times \frac{AWC_x}{P_x}$$

$$R_{xj} = k_{xj} \times \frac{ET_0}{P_x}$$

Y_{xj} is the annual water amount of land cover type j in grid cell x, $\mathrm{AE}T_{xj}$ is the actual evaporation amount of land cover type j in grid cell x, P_x is the precipitation of grid cell x. w_x is the non-physical parameter of natural climate-soil properties, R_{xj} is the Bydyko drying index, $\mathrm{AW}C_x$ is the effective soil moisture content of grid cell x, which is determined by soil depth and physical and chemical properties, K_{xj} is the vegetation evaporation coefficient of land cover type j in unit x, ET_0 is the reference evaporation coefficient

$$F = \frac{K}{Z}$$

Z is used as the coefficient representing the water flow. The more precipitation, the greater Z.F is the cost of water resources maintenance; K is a constant.

6. Analytic hierarchy process

Its mutual influence among the five factors, such as forest coverage will directly affect the quality of air and soil erosion, the distribution of the hydrological can also affect the degree of soil erosion, that is to say, the governance of the decline of the forest coverage rate of air quality is to a certain extent, governance or the degree of soil erosion

Table 1 Analytic hierarchy process

Cost Of Environmental Degradation	First-level indicators	second-level indicators
	Air quality	Carbon storage and carbon absorption
		Air pollutant

	vegetation	Forest coverage
	biodiversity	Habitat coverage
	water resource	Water pollution
	Land and soil	Land and soil resource loss degree

7. Scale Evaluation Model

Over time, the area of regional land use and its type will change gradually, so the environmental degradation caused by land use project cost may have a significant upward trend. Firstly, through the establishment of the CA - Markov model for regional land use types and the prediction of the corresponding area with time and space dimensions. We use existing data in land use to make corresponding predictions about the future so that we can conclude the ecological service assessment model corresponding to the function on the time dimension changes. Considering the impact of different land use projects on the ecological environment, according to $\Gamma(z) = \int_0^\infty t^{z-1}e^{-t}dt\ (0 < z < 1)$ (z is the scale factor),

the scale constant Q(z) is obtained, and the formula for calculating the scale is as follows:

$$\mathrm{Q(z)} = \Gamma(z) \times e^t \times \frac{S}{lnp}$$

Q(z) is the scale constant, S is the area of the region， p is the population density

$$F^\varepsilon = Q(z) \times F$$

F is the cost of environmental degradation that considers factors other than scale. F^ε is the cost of environmental degradation that considers scale factor.

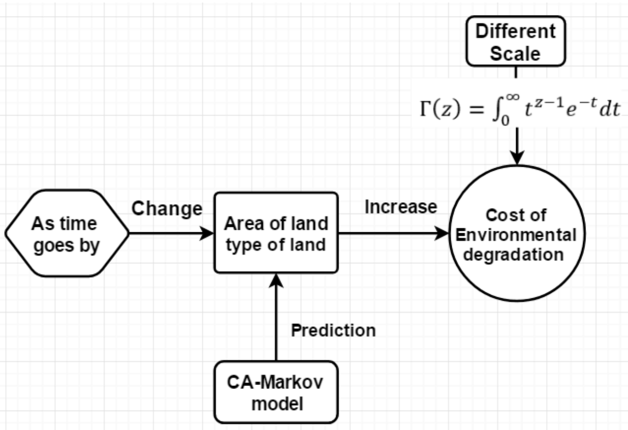

Figure 1

8. Advantages

The greatest advantage of the ecological services valuation model is the visual expression of the evaluation results. It solves the problem that the evaluation of ecosystem service function used to be abstract but not intuitive.

The InVEST model is able to grasp the overall layout, among which the sub-model, soil conservation model and water source model are very prominent, and therefore this paper make good use of this InVEST model to evaluate related aspects

Considering that it is beyond the ability of InVEST model to shows the results of biodiversity protection assessment in terms of economic value, the LCM model and GIS remote sensing technology is introduced to convert the biodiversity value assessment into the cost of habitat maintenance, which solves the problem that biodiversity cannot be quantified before.

Classify various factors to make the results more consistent with the actual situation. City-green model is applicable to a small area (a park, etc.), and it will conduct a structural analysis and ecological benefit evaluation on it. We hope to find out the influence of air quality and forest coverage rate changes within a small range, and the influence of soil and water source on the whole is relatively high, so InVEST model is adopted.

Analytic hierarchy process (AHP) can combine various factors together to obtain the overall cost of environmental degradation.

9. Conclusion

Modern economic theories tend to neglect its impact on the global biosphere, regarding the biosphere as a system with unlimited production capacity. The biosphere provides various kinds of natural processes to sustain the health of the environment, which is called ecosystem services. So, it is important to create an ecological services valuation model to understand the true economic cost of land use projects when ecosystem services are considered.

We choose different sub-models to evaluate different factors effectively. One of these sub-models named InVEST Model is used to evaluate water resources and land resources deficiencies. Another sub-model called CITY-green Model is used to calculate the maintenance costs of air quality decline and vegetation coverage reduction. Besides, LCM Model is used to evaluate the decline of biodiversity, and finally, comprehensive environmental degradation costs are obtained by multi-factor analysis.

We divide the aspects of environmental degradation into five categories: water pollution, air pollution, land pollution, vegetation coverage reduction, as well as biodiversity decline. We find that after the construction of the bridge, the severity of environmental degradation will increase in an exponential form. Only when a certain amount of money is invested in the effective maintenance of the ecological environment, can the ecological balance be maintained. Among these five aspects, the low forest coverage rate and soil and water loss caused by it are the main manifestations of environmental degradation, and the factors accounting for a higher proportion of environmental degradation costs. Therefore, project managers and developers should pay attention to avoid forest and reduce the cost of environmental degradation when planning land use projects.

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