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Optimal method of ecological restoration of degraded ecosystem using goal programming

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Abstract. Ecological restoration of degraded wetland ecosystem can be achieved by planning experts according to ground investigation, but with low efficiencies. We report that satellite sensors, maximizing ecosystem service values and minimizing ecological restoration cost improve ecological restoration efficiency. In particular, linear goal programming (LGP), an optimal programming, improves ecological restoration efficiency by more than 250% in the return on investment of ecological restoration, using TM satellite as area sensors. LGP also enables efficient introduction of optimal management into ecological restoration of degraded wetland ecosystem.

1 Introduction

Optimal ecological restoration of degraded wetland ecosystem (DWE) has received much attention in recent years due to the important ecosystem service values and economic benefits of DWE. DWE is abundant wetland resources with high tapping value. It has many possible uses in the agricultural field and has also been investigated as an exploitable ecosystem. However, DWE has been found to be too weak under optimal ecological restoration with satellite sensors to be protected and developed efficiently [1].

One way to toughen optimal ecological restoration of DWE is to incorporate a decision support model to improve return on investment and there has been extensive research regarding return on investment that maximize ecosystem services and minimize ecological restoration cost [2,3]. For example, Barton et al. showed that the decision support system could be prepared using optimization models based on cost-effectiveness [4] and more recently, Wainger et al. established such integrated optimization model [5]. However, although the effect of such decision support system on capturing the benefits of restoring ecosystem services of DWE was demonstrated over several years, little attention has been paid to maximizing return on investment of ecological restoration simultaneously by using satellite sensors.

The present paper presents an optimal model based on a linear goal programming (LGP) for maximizing return on investment of ecological restoration of DWE. On the basis of maximizing values of ecosystem services and minimizing ecological restoration cost simultaneously, according to status information of DWE from satellite sensors and subject to other constraints from planning DWE, it then describes an optimal assignment process of resource and ecological restoration investment of DWE. This combination of the resource and investment assignments formed a novel decision support model in which DWE was protected and developed efficiently.

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2 Material and methods

This study was undertaken in Dafeng City, Jiangsu Province, China in 1997. The site's coordinates are 32°56'-33°36' Latitude N and 120°13'-120°56' Longitude E. Average temperature is 14°C, while the average annual precipitation is 1042 mm. Dafeng boosted an area of DWE 77,300 hectares, including a variety of 11 DWE-use types that are cultivated land, forest land, breed aquatics pond, bare seawall, forest seawall, residential land, saltern land, grass land, bare land, beach reclamation for land and water reclamation for land.

The contradiction between protection and development of DWE in Dafeng was becoming more and more prominent. Conversion of terrestrial ecosystems resulting from DWE-use practice plays an important role in global carbon cycling. The ecosystem health indicators that can be observed by remote sensors include percent of cultivated land, forest land, breed aquatics pond, bare seawall, forest seawall, residential land, saltern land, grass land, bare land, beach reclamation for land and water reclamation for land. Changes in the DWE-use types, the value of ecosystem services also change. The increased population and intense development threaten and degrade wetland ecosystems of Dafeng, placing an elevated burden on Dafeng responsible for the planning and management of these sensitive areas.

The wetland ecosystem management of Dafeng frequently focuses on a variety of two objectives, e.g., to maximize the ecosystem service values, and minimize the ecological restoration cost. However, linear goal programming (LGP) provides a way of striving toward two such objectives simultaneously. The basic approach of LGP is to establish a specific numeric goal for each of the objectives, to formulate an objective function for each objective, and then to seek a solution that minimizes the ecological restoration cost and maximizes the ecosystem service values. Thus, the ecological management department of Dafeng had been assigned by the task of maximizing the ecosystem service values and minimizing the ecological restoration cost. The management of DWE was given to two factors: long-run ecosystem service values and the level of ecological restoration cost. In particular, management had established the goals of (1) maximizing the ecosystem service value and (2) minimizing the ecological restoration cost. However, the department realized that it probably will not be possible to attain the two goals simultaneously. Thus, the order in which the two goals of Dafeng were selected for linear programming was based on their assigned priorities. The job of maximizing the ecosystem service value was taken ahead of the job of minimizing the ecological restoration cost, and important job may be given precedence over others. Therefore, the use of priority-discipline models often provides a very welcome refinement over the more usual LGP.

On the other hand, the nearly cloud-free Landsat 5 TM image that covered the study area was acquired. After the image was examined for sensor errors, the digital numbers were converted to reflectance and rescaled to values between 0 and 100. The reflectance values were then adjusted for atmospheric scatter. The image was corrected for geometric error by transforming the image to a Universal Transverse Mercator (UTM) projection. The geometric transformation equation was computed using 48 ground control points. The spectral values for each pixel were interpolated using a nearest neighbour sampling approach and the data were output to a 30×30m pixel size. During the geometric correction process, the images were clipped to Dafeng political boundaries.

Otherwise, the wetland environments of Dafeng are characterized by erratic climate conditions and complex ecosystem types, challenging the applicability of remote sensing and geospatial technologies. The high humidity in wetland areas makes difficult to obtain the DWE-use map of Dafeng. The complex optical properties in wetland waters dilute the effectiveness of many algorithms for retrieving mud flat parameters that were originally developed for lands. The complex spectral signatures in wetland ecosystems make difficult to map and classify the DWE-use types. The presence of complex urban materials and croplands causes substantial inter-pixel and intra-pixel scenic changes, thus complicating the classification and characterization of the DWE-use types. Because a varying degree of spectral confusion was still observable in some areas, all 11 DWE-use types were identified using an image visual interpretation procedure through which spectral and spatial contextual contents as well as human wisdom and experience were synthesized. This image interpretation can be implemented digitally using on-screen digitizing, multiple zooming, and "area of interest" functionality. ERDAS, a commercial image processing software package (ERDAS, Inc., Norcross, GA, USA), was used for the visual interpretation. Thus, we conducted spectral enhancement of the image to maximize the visual separability by considering tones, colors, textures and shapes of the submerged vegetation along the coast. Specifically, we applied linear stretching, histogram equalization, Gaussian, standard deviations, and interactive stretching on the image to different objects in order to improve the recognition of DWE-use types. With the enhanced image, we further mapped the DWE-use types by using on-screen digitizing. That is, the map of DWE-use types was prepared through visual interpretation of Landsat-5 TM image in the form of screen prints of false colour composite (FCC) generated from bands 2, 3 and 4. Standard image interpretation characteristics such as tone, texture, shape size, pattern and association, along with sufficient ground truth and local knowledge, were followed to delineate different DWE-use types. This visual interpretation allowed us to analyze the DWE-use types and to compute their areas. Further, the satellite sensors-Landsat-5 TM sensors, as shown in Table 1, provided the area data of DWE-use types.

Table 1: Landsat-5 TM sensor specifications

Spectral bands	Spatial resolution	Overpass time
Blue: 0.45–0.52 um	30 m	10:30 am MST
Green: 0.52– 0.60 um	30 m	10:30 am MST
Red: 0.63–0.69 um	30 m	10:30 am MST
NIR: 0.76– 0.90 um	30 m	10:30 am MST
SWIR: 1.55– 1.75 um	30 m	10:30 am MST
SWIR: 2.08– 2.35 um	30 m	10:30 am MST
Thermal: 10.4– 12.5 um	120 m	10:30 am MST

Further, the procedure is to calculate return on investment of ecological restoration of DWE by means of the following formula:

$$ROI = \max\left(\frac{V1}{V2}\right) = \frac{\max V1}{\min V2} \tag{1}$$

The formula is actually to solve a LGP as follows.

$$ROI = \min V2 = \sum_{i=1}^{11}\sum_{j=1}^{11} C_{i,j} X_{i,j} \tag{2}$$

Subject to:

$$\sum_{i=1, i\neq j}^{11} X_{i,j} = \left| X_{j,j}^{V1} - \hat{X}_{j,j} \right| \tag{3}$$

$$\sum_{j=1, j\neq i}^{11} X_{i,j} = \left| X_{i,i}^{V1} - \hat{X}_{i,i} \right| \tag{4}$$

$$X_{i,j} \geq 0 \tag{5}$$

$$\max V1 = \sum_{i=1}^{11} P_i X_{i,i} \tag{6}$$

Subject to:

$$X_{2,2} + X_{5,5} \geq 0.2\hat{X} \tag{7}$$

$$X_{1,1} + X_{8,8} + X_{9,9} + X_{10,10} \geq 0.57\hat{X} \tag{8}$$

$$X_{3,3} + X_{11,11} \geq 0.17\hat{X} \tag{9}$$

$$X_{1,1} + X_{2,2} + X_{3,3} + X_{4,4} + X_{5,5} + X_{8,8} + X_{10,10} + X_{11,11} \geq 0.9\hat{X} \tag{10}$$

$$\sum_{i=1}^{7} X_{i,i} P_i - \sum_{i=8}^{11} X_{i,i} P_i \leq 0 \tag{11}$$

$$\sum_{i=1}^{7} X_{i,i} - \sum_{i=8}^{11} X_{i,i} \leq 0 \tag{12}$$

$$\sum_{i=1}^{11} X_{i,i} = \hat{X} \tag{13}$$

$$X_{i,i} \geq 0 \tag{14}$$

$$C_{i,i} = 0 \tag{15}$$

$$i = 1,\ldots,11;\ j = 1,\ldots,11 \tag{16}$$

where $\max V1$ is maximizing the values of ecosystem services of DWE by changing DWE-use types, $\min V2$ is minimizing cost of ecological restoration in given $\max V1$ condition,

$X_{i,j}$ =area of *i*th use type converted to *j*th use type,

$C_{i,j}$ =cost of area of *i*th use type converted to *j*th use type,

$X_{i,i}^{V1}$ =optimization planning area of *i*th use type,

$\hat{X}_{i,i}$ =real area of *i*th use type,

$X_{j,j}^{V1}$ =optimization planning area of *j*th use type,

$\hat{X}_{j,j}$ =real area of *j*th use type,

$P_i = X_{i,i}$'s ecosystem service value, $i = 1,\ldots,11$,

$X_{1,1}$ = area of cultivated land,

$X_{2,2}$ = area of forest land,

$X_{3,3}$ = area of breed aquatics pond,

$X_{4,4}$ = area of bare seawall,

$X_{5,5}$ = area of forest seawall,

$X_{6,6}$ = area of residential land,

$X_{7,7}$ = area of saltern land,

$X_{8,8}$ = area of grass land,

$X_{9,9}$ = area of bare land,

$X_{10,10}$ =area of beach reclamation for land,

$X_{11,11}$ =area of water reclamation for land,

$\hat{X}$ =total area of DWE,

$0.2\hat{X} \wedge 0.57\hat{X} \wedge 0.17\hat{X} \wedge 0.9\hat{X}$ =plan revealed by Dafeng municipal government,

$P_1 = 0.92 \times 10^4 \$ km^{-2}$,

$P_2 = 2.61 \times 10^4 \$ km^{-2}$,

$P_3 = 0.04 \times 10^4 \$ km^{-2}$,

$P_4 = 0.20 \times 10^4 \$ km^{-2}$,

$P_5 = 1.31 \times 10^4 \$ km^{-2}$,

$P_6 = 0.00 \times 10^4 \$ km^{-2}$,

$P_7 = 0.04 \times 10^4 \$ km^{-2}$,

$P_8 = 2.32 \times 10^4 \$ km^{-2}$,

$P_9 = 0.01 \times 10^4 \$ km^{-2}$,

$P_{10} = 0.23 \times 10^4 \$ km^{-2}$,

$P_{11} = 0.04 \times 10^4 \$ km^{-2}$,

$C_{1,2} = 1.00 \times 10^4 \$$,

$C_{1,8} = 0.40 \times 10^4 \$$,

$C_{3,2} = 1.30 \times 10^4 \$$,

$C_{3,8} = 0.60 \times 10^4 \$$,

$C_{9,2} = 1.20 \times 10^4 \$$,

$C_{9,8} = 0.50 \times 10^4 \$$.

Table 2: Real use and optimization planning of DWE (area, *km*^{2})

Use type	Real use	Planning
$X_{1,1}$	161.40	50.11
$X_{2,2}$	0.86	69.56
$X_{3,3}$	106.47	55.69
$X_{4,4}$	4.15	4.15
$X_{5,5}$	10.54	10.54
$X_{6,6}$	1.80	1.80
$X_{7,7}$	8.37	8.37
$X_{8,8}$	53.95	153.59
$X_{9,9}$	31.98	25.72
$X_{10,10}$	8.53	8.53
$X_{11,11}$	12.38	12.38
Total value of ecosystem services=305.99$\times 10^4$\$		

3 Results

The optimal solution for LGP using the above data is shown in Table 2 and 3. The data “Real use” of Table 2 was provided by Landsat-5 TM sensors. Table 2 shows the relationship between real use and optimal planning of DWE. The first column of Table 2 summarizes the components of the 11 Use types of DWE where $X_{i,i}, i = 1,\ldots,11$ devotes 11 rows to describing the cultivated land, forest land, breed aquatics pond, bare seawall, forest seawall, residential land, saltern land, grass land, bare land, beach reclamation for land and water reclamation for land. The second column then introduces each real use area of the 11 Use types of DWE. The last column indicates each planning area of the 11 Use types of DWE. For the production of the second column areas the Landsat 5 TM image was classified using the visual interpretation procedure as described above. The classification results were then used to create the areas. The linear programming procedure was used to generate the last column areas. The ecosystem health indicators that can be observed by remote sensors include percent of impervious areas, natural vegetation cover, wetland loss and fragmentation, wetland biomass change. Thus, the area of grass land ($X_{8,8}$) increased dramatically with the decease the area of cultivated land ($X_{1,1}$) and breed aquatics pond ($X_{3,3}$). Return on investment of ecological restoration of DWE is given by

$$ROI = \max\left(\frac{V1}{V2}\right) = \frac{\max V1}{\min V2} = \frac{305.99}{119.34} = 256.41\%$$

An examination of Table 2 and 3 shows that a definite relationship exists between ecosystem service value and ecological restoration cost in DWE. Table 3 lists the ecological restoration planning. For example, the $X_{1,2}$=68.70 represents that the 68.7 square kilometres of the cultivated land is converted to the forest land. The $X_{1,8}$=42.60 represents that the 42.6 square kilometres of the cultivated land is converted to the grass land. The $X_{3,8}$=50.78 represents that the 50.78 square kilometres of the breed aquatics pond is converted to the grass land. The $X_{9,8}$=6.26 represents that the 6.26 square kilometres of the bare land is converted to the grass land. The return on investment of ecological restoration of DWE increases with the increase in ecosystem service value and the decrease in ecological restoration cost. By increasing forest and grass land areas and reducing cultivated land and breed aquatics pond areas, ecological restoration can produce up to \$256 for every \$1 invested. It indicates that the ecological restoration technology has low investment and high-efficiency.

Table 3: Optimization planning for ecological restoration of DWE (area, km^2)

Restoration type	Planning area
$X_{1,2}$	68.70
$X_{1,8}$	42.60
$X_{3,2}$	0.00
$X_{3,8}$	50.78
$X_{9,2}$	0.00
$X_{9,8}$	6.26
Total investment	119.34×10^4\$

4 Conclusion

In this paper we specify satellite sensors and LGP and discuss the application strategies in optimal ecological restoration of DWE. This paper aims to balance between economic development and protection of wetland ecosystem. This balance covers the full cycle of information collection, planning, decision making, management and monitoring of the ecosystem. However, uncertainties exist in almost all these activities in this cycle. This balance is a dynamic, multi-disciplinary and iterative process to promote sustainable management of ecosystem. The first is a benchmark model for finding the types of DWE uses at maximizing the values of ecosystem services of DWE. The second is constructed to find the investment patterns for minimizing cost of ecological restoration of DWE. Our results provide compelling evidence that there could be a relationship between development and ecological restoration of DWE and suggest that this approach appears to be effective as an eco-economic indicator for ecological restoration investment management actions that maximize ecosystem services of DWE. Thus, we recommend that these results be repeated using a wider range of satellite sensors. Experiments similar to those reported here should be conducted using different degraded wetland ecosystems.

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