supplementary materials for

# Integrating ecosystem services value and economic benefits for sustainable land-use management in semi-arid region in northern China

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## 1. The biophysical factors that are used as constraint factors

Tab. S1 The physical and environmental factors that are used as constraint factors

| | **biophysical factors** |
|---|---|
| Meteorology | Accumulated temperature during growing season, Accumulated precipitation during growing season, Mean annual precipitation, Mean annual temperature |
| Soil | Soil organic matter, Soil total nitrogen, Soil texture |
| Topography | Elevation, Aspect, Slope |
| Traffic conditions | Euclidean distance from the road, Euclidean distance from residential area |

## 2. A brief description of how the CLUE model works

(1) Determine the demand of different land use departments;

(2) Determine the suitability value Pi according to the biophysical factors and the binary regression model (Eq.3 in manuscript);

(3) Determine the suitability value of land use Si (Eq.3 in manuscript) according to the fuzzy membership function;

(4) Determine the stability value Ei (Eq.3 in manuscript) according to the transition matrix of the land use type;

(5) Using the theoretical framework of the CLUE-S model, we simulated land-use changes and calculated the total probability graphs of land use for all types.

(6) Then, we transferred the total probability graph to a point layer, exported the attributes to Excel, and combined the attributes with the demands of land use to sort and calculate the different land-use types via hierarchical decision making. The spatial probability distribution and the transforms rule refer to the parameters in the Taipusi research from Liyue [67] (reference in manuscript).

(7) Because the space of land use is allocated by the total probability of land use and the demand area, according to the final iterative result, we returned the grid dot back to the grid layer to construct the spatial patterns of land use under different scenarios.

## 3. Evaluation of land-use economic benefits coefficients

### 3.1 Evaluation of land-use economic benefits

The land-use economic benefit was accounted by using hierarchical analysis and entropy method in combination with the land-use economic benefit assessment indicator system (Chen et al., 1998; Zhang et al., 2004; Jiao et al., 2006). The socioeconomic data came from the statistics yearbook provided by the Taipus Bureau of Statistics.

### 3.1.1 Evaluation index system of land-use economy

According to the current situation of the Taipus Banner, the land use types that can produce economic benefits are divided into four categories, including cropland, forest, grassland and built-up.

The income from agriculture, forestry and animal husbandry can directly reflect the economic output level, so the income is also the most critical factor to measure the economic benefit of land use.

According to the principles of science, comprehensiveness and feasibility, 16 indicators were selected based on the literature to construct an index system for evaluating the economic benefits of land use (Tab. S2).

Tab. S2 Evaluation index of economic benefits of land-use

| Primary evaluation objectives | Secondary evaluation objectives | Evaluation index | units |
|---|---|---|---|
| Economic benefits of land use | Economic benefits of cropland | Agricultural income (X1) | Ten thousand yuan |
| | | Average agricultural output value (X2) | ten thousand yuan/hm$^2$ |
| | | Labor productivity in the primary industry (X3) | Ten thousand yuan/person |
| | | Food production per unit (X4) | kg/hm$^2$ |
| | | Average cost of agricultural production (X5) | Ten thousand yuan/hm$^2$ |
| | Economic benefits of forest land | Forestry income (X6) | Billion yuan |
| | | Average forestry output value (X7) | Ten thousand yuan/hm$^2$ |
| | | Labor productivity in the primary industry (X3) | Ten thousand yuan/person |
| | | Average cost of forestry production (X8) | Ten thousand yuan/hm$^2$ |
| | Grassland economic benefits/ Economic benefits of grasslands | Animal husbandry income(X9) | Ten thousand yuan |
| | | Average animal husbandry output value (X10) | Ten thousand yuan/hm$^2$ |
| | | Labor productivity in the primary industry (X3) | Ten thousand yuan/person |
| | | Livestock yield per unit (X11) | Head/hm$^2$ |
| | | Average cost of Animal husbandry (X12) | Ten thousand yuan/hm$^2$ |
| | Economic benefits of built-up | Gross output of secondary and tertiary industries (X13) | Ten thousand yuan |
| | | Average output value of secondary and tertiary industries (X14) | Ten thousand yuan/hm$^2$ |
| | | Labor productivity in the secondary and tertiary industries (X15) | Ten thousand yuan/person |

| | | |
|---|---|---|
| | Average investment intensity of construction land (X16) | Ten thousand yuan/hm$^2$ |

The index system consists of three levels: first level target, second level target and evaluation index. The first-level target layer is the economic benefits of village-level land use in Taipus Banner, and the second-level target layer is the economic benefits of cultivated land, woodland, grassland and construction land.

**3.1.2 Evaluation methods**

(1) Standardization of indicators

According to the evaluation index system of economic benefit of land use, the social and economic statistics of Taipus Banner from 1995 to 2008 were sorted and calculated to obtain the original data of indicators from 1995 to 2008. Among them, the missing values were replaced by the mean of the adjacent two years. In order to eliminate the dimensions and strengthen the comparability of various indicators at the same level, the original data were first standardized and pre-processed. This study adopts the means of Standardization of Data Range for normalization, and uses the standardized data as the basis of economic benefit evaluation. The standardized formula is:

$$Y_{ij} = (X_{ij} - X_{jmin})/(X_{jmax} - X_{jmin}) \qquad (1)$$

Where Xij represents the original value of the jth evaluation index of the ith evaluation object, Yij represents the standard value of the jth evaluation index of the ith evaluation object and Xjmax and Xjmin respectively represent the largest original value and the smallest original value in the jth index. The standardized data of Taipus Banner indicators from 1995 to 2008 are used for the subsequent evaluation.

(2) Determination of indicator weight

This study uses the Entropy Method to determine the weight of each evaluation factor in the index system as the results of the Entropy Method avoid the subjective influence on the weight determination. The specific steps are as followed:

(a) Set the original index value as Xij, calculate the weight of the j$^{th}$ index value of the i$^{th}$ object, and perform comprehensive standardization of the indexes.

(b) Calculate the entropy value of the jth index and record it as ej.

$$e_j = -k\sum_{i=1}^{n} P_{ij} * \ln P_{ij} (k = 1/\ln n, 0 \le ej \le 1) \qquad (2)$$

Where Pij is the value obtained after comprehensive standardization.

(c) Calculate the difference coefficient of the j$^{th}$ index ($g_j$).

$$g_j = 1 - e_j \quad (3)$$

A larger gj value indicates higher index importance.

(d) Determine the index weight $W_j$.

The comprehensive weight and weights for different land-use types of economic benefits of land-use in Taipus banner from 1995 to 2008 are shown in Tab. S3.

Tab. S3 Weighted value of factors for economic evaluation of land use

| Land-use type | Cropland | | | | | Forest | | | |
|---|---|---|---|---|---|---|---|---|---|
| | X1 | X2 | X3 | X4 | X5 | X3 | X6 | X7 | X8 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Land-use based weight | 0.2468 | 0.4568 | 0.1740 | 0.1172 | 0.0052 | 0.0284 | 0.4787 | 0.4924 | 0.0004 |
| Comprehensive weight | 0.0773 | 0.1430 | 0.0545 | 0.0367 | 0.0016 | 0.0065 | 0.1090 | 0.1121 | 0.0001 |
| | Grassland | | | | | Built-up | | | |
| Land-use type | X3 | X9 | X10 | X11 | X12 | X13 | X14 | X15 | X16 |
| Land-use based weight | 0.2392 | 0.3352 | 0.4142 | 0.0000 | 0.0114 | 0.3320 | 0.3317 | 0.3363 | 0.0000 |
| Comprehensive weight | 0.1062 | 0.1488 | 0.1839 | 0.0000 | 0.0050 | 0.0051 | 0.0051 | 0.0052 | 0.0000 |

### 3.2 Economic benefit coefficient

The weighted sum of different indicators and weights can get the final economic benefits of land use. The economic benefit of land use divided by the corresponding land use area can get the economic benefit coefficient of different land use types (Table 1 in the main text).

The data collected from Bureau of Land Resources in Taipusi was used to provide the trend that used to predict the economic indices in Sc5. The R square values of the regression coefficient of determination were 0.8025 and 0.8712 in the simulation between agricultural income, animal husbandry, and year, indicating a good relationship between income and time in the Banner scale

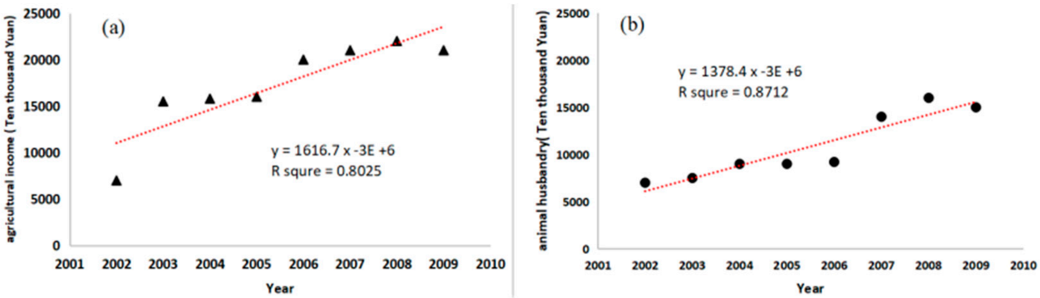


**Fig. S1** The relationship between income and time. (a) is the relationship between agricultural income and time; (b) is the relationship between animal husbandry income and time.

### 4. The illustration of the terms about ecosystem services used in evaluation of ecological benefits

**(1) NPP.** Net primary productivity (NPP) and biomass are two important indicators reflecting the production of organic matter. Biomass reflects the storage of organic matter, and primary productivity reflects the quality of organic matter produced at a certain time period (such as a year). NPP simulated by Terrestrial Simulation model (TESim) (Jiang et al., 2014) is used to obtain the value of primary production of ecosystem in the study area according to the unit mass value of organic matter.

**(2) The regulation of carbon dioxide and oxygen.** In the evaluation of ecosystem's two service functions of fixing carbon dioxide and releasing oxygen, according to the reaction equation of photosynthesis and respiration, the amount of carbon dioxide needed to form 1 g dry matter (generally 1.62 g) and the amount of oxygen released (generally 1.2 g) were calculated. Then the carbon tax method is used to estimate the functional value of absorbing carbon dioxide, and the industrial oxygen method is used to estimate the functional value of releasing oxygen.

**(3) Nutrient cycling in the ecosystem.** Vegetation in ecosystems can absorb nutrients during growth. These nutrients matter recycling through complex food webs has become an indispensable part of the global biogeochemical cycle. When evaluating the role of ecosystem in nutrient cycling, the annual uptake of nitrogen, phosphorus and potassium in ecosystem was estimated based on NPP. Then, price of the corresponding fertilizer is calculated according to the statistical data.

**(4) Water conservation.** Water conservation is an important function of ecosystem. Water conservation refers to the process and ability of the ecosystem to retain water fully in the system through interception, infiltration and storage of precipitation through forest canopy, litter layer and soil layer, lakes and reservoir water bodies within a certain time and space. It not only meets the demand for water resources within the system, but also provides water resources to the external and middle and lower reaches. The calculation formula is precipitation minus evaporation, transpiration and runoff.

**(5) Soil conservation.** According to the Classification standard of soil erosion issued by the Ministry of Water Resources, soil erosion includes the value of reducing land loss area, reducing soil fertility loss and reducing sediment deposition, this value can be calculated by the amount of soil erosion and soil organic matter simulated by TESim.

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