Journal of Geographical Sciences 15, 1 (2005) 44-52 ISSN: 1009-637X www.geog.cn

Ecological footprint analysis based on RS and GIS in arid land

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Abstract: Sustainable development has become a primary objective for many countries and regions throughout the world now. The ecological footprint (EF) is a kind of concise method of quantifiably measuring the natural capital consumption and it can reflect the goal of sustainability. In this paper, the concept, the theory and method of ecological footprint are introduced. On this basis, the study brings forward the method of ecological footprint and capacity prediction. The method is employed for the ecological footprint prediction combining consumption model with population model and the technique is adopted for the ecological capacity (EC) prediction uniting the Geographical Cellular Automata (Geo CA) and Geographic Information System (GIS). The above models and methods are employed to calculate EF and EC in 1995 and 2000 and predict them in 2005 in Hexi Corridor. The result shows that EF is continually increasing, and EC ascended in the anterior 5 years and will descend in the posterior 5 years. This suit of method is of the character of accuracy and speediness.
Key words: RS; GIS; Cellular Automata; ecological footprint; arid land; Hexi Corridor
doi: 10.1360/gs050106

1 Introduction

In recent years the ecological footprint (EF), originally developed by Wackernagel and Rees in the mid-1990s (Wackernagel and Rees W, 1996; 1997), has gained much attention in Ecological Economics. This method tracks natural resources consumption of a nation or a region and translates them into biologically productive land area, which is required to produce the resources and to assimilate the wastes. EF calculation should be based on different scales (global, national, regional, urban or individual) of consumption. And then we can compare the EF and the ecological capacity (EC) of the same scale to determine the ecological status of this scale. Most of the researchers used statistical data and models to calculate EF and EC; however, the precision and computational efficiency of the statistic models are low and problematic. Moreover, the theory and methodology of EF and EC prediction have not been developed in literature so far. This paper is one of the few quantitative studies of EF and EC predictions. It takes Hexi Corridor as an example to illustrate the EF modeling based on economical data and remote sensing (RS) techniques. The EF model in this paper integrates the individual consumption level and population and its structure. Also RS and Geographic Information System (GIS) have been coupled to calculate EC. At the same time, the prediction models of EF and EC are proposed in this paper to accommodate decision-making on sustainable development of ecosystem. The method introduced here are not only efficient and precise in computation, but capable of predicting the future scenarios. There are five sections in this paper. The first one introduces the methodology of the model in this paper. Section 2 introduces the concept of the ecological footprint and presents the methodological framework and theory. The third section addresses how to improve calculation and prediction method of EF and EC. The forward models of EF and EC and their prediction will be dealt with in Section 4, and the advantages and disadvantages of the proposed method are discussed in the final section.

Received: 2004-09-26 **Accepted:** 2004-11-20
Foundation: Knowledge Innovation Project of CAS, No.KZCX-10-09; Project of Office of the Leading Group for Western Region Development of the State Council, No.[2002]11
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2 Methodological foundations

2.1 Concept of the ecological footprint

The ecological footprint analysis was proposed to evaluate sustainability by Canadian ecological economists Rees and Wackernagel in the early 1990s. The ecological footprint was defined as the amount of bio-productive land required to support the consumption of a given population at current consumption level, and the ecological capacity is related to the amount of bio-productive land to provide the resources and to assimilate the wastes in a defined habitat without permanently damaging the ecosystem.

Based on the following certainties, sustainable development is scaled by human consumption of the amount of resources. First of all, human must consume all varieties of products and services from the nature to maintain human subsistence. Also, the amount of any consumption can be converted to the area of bio-productive land that has capacity to produce primal matter and energy for the consumption. By large, the EF of a defined population can be compared with the area of land available on a global or regional scale, usually referred to as the 'ecological capacity'. If the EF is greater than the available EC, which is often referred to as ecological deficit (ED), it indicates that the EC cannot carry human's load in this region. To meet the demand of the current consumption levels, there are two means that can be adopted: consuming the stocking of the natural capital or importing scarce resources. Both indicate that the mode of the regional development is unsustainable. If the EF is smaller than the EC, it is often interpreted as ecological surplus (ES), which indicates that human's load is within the ecological capacity in this region and EC will expand correspondingly so that the mode of the regional development is sustainable.

2.2 Calculation models of the ecological footprint

The EF model is mainly used to calculate the area of bio-productive land that is used to maintain consuming resources and assimilating wastes in the condition of certain population and economic scale. A basic hypothesis about the EF is that all kinds of land are repulsive in space. Area of every kind of bio-productive land can be accumulated in this assumption and the formula of the EF is:

$$EF = N \bullet (ef) = N \bullet \sum w_i a_i = N \bullet \sum w_i (c_i / p_i) \quad (1)$$

where EF is the total ecological footprint, N is the number of population, ef is per capita ecological footprint, i is the type of consumption, w_i is equivalence factor, a_i is per capita area of bio-productive land to produce the i-th consumption, c_i is per capita amount of the i-th consumption, and p_i is the global average production capacity of the i-th consumption. From equation (1), we can see that the EF is a function of the number of population and per capita consumption, or the EF equals to the product of the equivalence factor and the sum of area of bio-productive land for every kind of consumption.

Note worthily, the yield and the equivalence factors should be taken into account simultaneously when the EC is calculated, and its calculation equation is as follows.

$$EC = \sum y_i w_i A_i \quad (2)$$

where EC is the total ecological capacity, y_i is the yield factor, and A_i is the total area of bio-productive land to produce the i-th consumption.

3 Modified methodology

Hexi Corridor, located in the northwest of Gansu province, China, is selected as a study area in this paper. It ranges from Mountain Wushaoling to the border of the Xinjiang Uygur

Autonomous Region, containing cities of Wuwei, Zhangye, Jiuquan, Jinchang and Jiayuguan in regionalism. There are two reasons accounting for the selection of Hexi Corridor as the study area. First of all, this region is a relatively independent geographical unit and to a certain extent free of interference of other factors. In addition, it is of certain representativeness in arid land use. Secondly, the strategies and policies of western development provide Hexi Corridor many unprecedented opportunities and economic development conditions of this region. However, the excessive development over a long period of time, the inherent arid and water-deficient climatic condition as well as vulnerable ecosystem make the region's eco-environment increasingly deteriorate. It is thus crucial to study the EF and ecological status of this region so as to achieve harmonious development.

3.1 Data collection

According to the study demand and the actual situation of this region, the following data have been collected: (1) Gansu Province Statistical Yearbook 1996 and 2001; (2) China Population Statistical Yearbook 1990-2000, Gansu Province Population Census Statistics 2000; (3) Gansu Province 1:100,000 Land Use Data 1995 and 2000; (4) Gansu Province 1:1,000,000 Soil Type and Soil Texture Data; (5) Gansu Province 1:250,000 Elevation Data; (6) Gansu Province 1: 1,000,000 Relief Data; and (7) from meteorological stations throughout Gansu Province.

3.2 Modified method and its procedure

In this paper, the statistical data of an individual are used to calculate the EF. The objects of consumption are divided into rural inhabitants and urban ones allowing for different consumption levels of these two groups in China. The combination of RS and GIS technologies are applied to calculate the EC. This method is of the character of accuracy and speediness comparing with the statistical data applied to the same issue. The theory and method of the EC and the EF prediction are brought forward for the first time in this paper. Meanwhile, the consumption and population models are applied to predict the EF and both models account for the increase of living level and population change in the prediction process. To predict the EC, in the process of land use prediction, historical data of land uses, natural factors such as soil, climate and geomorphy and human factors including economy, technology and policy have been considered.

4 Calculating of EF and EC in Hexi Corridor

4.1 EF calculation

Based on the theory and methodology of the EF, per capita EF of Hexi Corridor in 1995 and 2000 are calculated by employing the data about per capita consumption and structure of total consumption in Gansu Province Statistical Yearbook 1996 and 2001. Owing to the great discrepancy on consumption levels between urban residents and their counterparts in rural areas in China, per capita rural and urban consumption levels are calculated separately.

The EF is mainly composed of two parts: consumption of biological resources and energy

Table 1 Calculation result of the EF in Hexi Corridor

Land type	Equivalence factor	Per capita EF of rural residents				Per capita EF of urban residents			
		Per capita area ($ha \cdot cap^{-1}$)		Equivalence area ($ha \cdot cap^{-1}$)		Per capita area ($ha \cdot cap^{-1}$)		Equivalence area ($ha \cdot cap^{-1}$)	
		1995	2000	1995	2000	1995	2000	1995	2000
Arable land	2.8	0.2940	0.2936	0.8232	0.8221	0.4547	0.4722	1.2731	1.3221
Forest	1.1	0.0341	0.0300	0.0375	0.0330	0.1940	0.2445	0.2134	0.2690
Pasture	0.5	0.3972	0.4272	0.1986	0.2136	1.9964	2.0922	0.9982	1.0461
Water	0.2	0.0106	0.0063	0.0021	0.0013	0.2820	0.3105	0.0564	0.0621
Energy land	1.1	0.1526	0.1529	0.1679	0.1682	0.4717	0.5129	0.5189	0.5642
Built-up land	2.8	0.0126	0.0310	0.0353	0.0867	0.0381	0.0456	0.1066	0.1278
Total	—	—	—	1.2646	1.3249	—	—	3.1666	3.3913

use. Biological resources mainly include farm produces such as grain crop, cotton, vegetable and fruit, forest products like lignum, nut, and fruit, animal products such as meat, egg, milk and fur, aquatic products including but not limited to fish, shrimp and seashell. These produces and products are converted to the area of bio-productive land. We used the same method as the one used by the Food and Agriculture Organization of United Nations (FAO) in 1993 to calculate the world average yield data of biological resources to do such a conversion so that the results from the same standard are comparable with other regions or countries. In the part of energy use, statistical data of all consumed energy including coal, coking coal, fuel oil, crude oil, gasoline, diesel oil and electric power are transformed into the area of fossil energy land by the international average heat productivity criterion of unit fossil energy land area.

To get an accurate calculation, biological resources and energy consumption in the region have to be computed accurately. The data in this paper are based on the individual consumption, so that the consumptions of the society and government should be taken into consideration. Then, the total consumption is shared by the consumption ratio of rural and urban population. This manner of data processing can avoid errors effectively.

Based on the above data processing method, all kinds of bio-productive land area from the calculation of biological resources and energy consumptions in Hexi Corridor are added, and then we multiply all types of the productive land area by equivalence factors to get per capita EF of rural and urban residents in Hexi Corridor in 1995 and 2000 in the unit of the world average ecological space (Table 1). The total EF in this region is obtained by multiplying per capita EF of rural and urban residents by their respective populations. If we divide the total EF by the number of population in Hexi Corridor, per capita EF of Hexi Corridor in 1995 and 2000 are obtained and the values are 1.6902 and 1.8342 ha•cap^{-1}. From the above calculation, we can say that the EF is an indicator of the resources status available for an individual person. Because of the variations of population structures from region to region, the total EF can vary dramatically. To compare the total EF of any region, we should calculate it on the basis of the number and structure of this region's population and per capita EF. The total EF of the whole study area is a summation of per capita EF of rural and urban residents multiplied by their respective population.

4.2 EC calculation

The data of land use are obtained by interpreting the remote sensing images in Hexi Corridor in 1995 and 2000. Areas of all kinds of land use such as arable land, forest, pasture, waters, and built-up land are calculated. The total area of land is divided by the population in Hexi Corridor, and multiplied by corresponding equivalence and yield factors to obtain per capita EC of the Hexi Corridor. The calculation results are shown in Table 2. The summation of the areas of all kinds of land use in every county is multiplied by the equivalence and yield factors to obtain the EC of the whole study area. Following the same procedure, the total EC can be calculated for other regions and counties. Based on the proposal by World Commission on Environment and Development (WCED) in the report *Our Common Future*, it should take away 12% of the

Table 2 Calculation result of the EC in Hexi Corridor

Land type	Total area (ha)		Area of per capita (ha·cap^{-1})		Equivalence	Yield	Equivalence factor (ha·cap^{-1})	
	1995	2000	1995	2000	factor	factor	1995	2000
Arable land	1146410.26	1197797.99	0.2601	0.2602	2.8	1.66	1.2089	1.2091
Forest	707415.79	673646.10	0.1605	0.1463	1.1	0.91	0.1607	0.1464
Pasture	4453854.54	4546313.62	1.0105	0.9874	0.5	0.19	0.0960	0.0938
Water	33915.72	34109.32	0.0077	0.0074	0.2	1.00	0.0015	0.0015
Energy land	0	0	0	0	1.1	—	0	0
Built-up land	91883.62	108335.25	0.0208	0.0235	2.8	1.66	0.0967	0.1092
total	—	—	—	—	—	—	1.5638	1.5600

Note: The numbers of population are respectively 4,407,575 and 4,604,553 in Hexi Corridor in 1995 and 2000 bio-productive land area from EC to protect biodiversity. The values of per capita EC in 1995 and 2000 are 1.3761 and 1.3728 ha•cap^{-1} after the deduction of 12% of per capita EC of the productive land area.

4.3 EF and EC prediction models

4.3.1 EF prediction The prediction of EF should take into account two main points: one is the prediction of per capita consumption level, the other is the prediction of the number of population. The former reflects the increase of per capita EF, and the combination of both indicates the increase of the total EF in this region. The EF means the area of productive land possessed by human, and the bio-productive land can produce consuming goods and services while the consumption of them can be scaled by monetary consumption level. Without consideration of the rise of price, the improvement of consumption may reflect the increase of EF since they are directly proportional to each other. The total EF of a region is the product of per capita EF and the population in this region. The predictions of the consumption level and population are introduced as follows.

(1) The prediction of consumption level

First, the solution procedure of the equation: The rural and urban expenditures and price indices from 1990 to 2000 are obtained from the Gansu Province Statistical Yearbook 2001, and the population data in those years are obtained from the China Population Statistical Yearbook 1990-2000. The actual consumption levels from 1990 to 2000 can be calculated through dividing the expenditure of each year by the price index of 1978, and then splitting it by the rural and urban population to get their per capita actual consumption level from 1990 to 2000. The data of per capita actual consumption level of urban residents and time exhibit a linear trend (Figure 1).

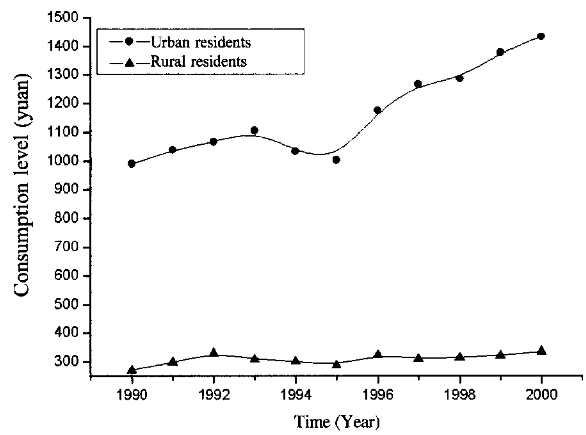

Figure 1 Actual consumption level over the years after the deduction of the element of price rise in Hexi Corridor

Suppose the trend line is:

$$\hat{y}_t = \hat{\alpha} + \hat{\beta}(t - \bar{t}) \tag{3}$$

then the least-squares procedure is employed to calculate $\hat{\alpha}$ and $\hat{\beta}$, which gives the following results about the consumption level of urban residents.

$$\hat{y}_t = 1161.47 + 42.75\,(t - 1995) \qquad t = 1990\cdots2000 \tag{4}$$

Similarly, the regression equation about the consumption level of rural residents is

$$\hat{y}_t = 309.79 + 3.69\,(t - 1995) \qquad t = 1990\cdots2000 \tag{5}$$

Second, the quality test of the equation: After the regression model is constructed, we should test its credence and identify its quality. The F-test is employed to test its accuracy and quality of this linear regression.

In the process of regression analysis, the difference of n observed values about y may be showed by the total sum of squares of deviations. That is

$$S_{\text{Total}} = L_{yy} = \sum_{i=1}^{n}(y_i - \bar{y})^2 = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 + \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2 = Q + U \tag{6}$$

where Q is the summation of error square, and U is the sum of regression square.

From Equation (6), we can see that when the variable U increases and Q decreases, the accuracy of regression equation increases. The numerical value of variable F can be used to judge the quality of the regression equation.

$$F = U \Big/ \frac{Q}{n-2} \tag{7}$$

The variable F obeys F distribution with the freedom $f_1 = 1$ and $f_2 = n - 2$. That is

$$F \sim F(1, n-2) \tag{8}$$

When the confidence level is α, if F is greater than F_α $(1, n-2)$, then the effect of regression equation is notable. If F is smaller than $F_{0.10}$ $(1, n-2)$, the effect of regression equation is usually not notable. For the regression equation of per capita consumption level of rural residents, as confidence level α is 0.01, and F is greater than $F_{0.01}$ (1, 9), so the effect of regression equation is remarkable ($\alpha = 0.01$).

In the same fashion, for the regression equation of per capita consumption level of rural residents, as confidence level α is 0.05 and F is greater than $F_{0.05}$ (1, 9), the effect of regression equation is remarkable ($\alpha = 0.05$).

Finally, the calculation result: In brief, the regression equation of consumption level of rural and urban residents meets the significance test condition and the two formulae can fit the actual status very well. We extrapolated the two equations in time and predicted the consumption level of rural and urban residents in 2005. The final consumption level of the rural and urban residents are 346.69 and 1588.97 yuan, respectively, which are 1.030 and 1.109 times of those in 2000. Similarly, per capita EF are 1.3646 and 3.7610 ha•cap^{-1} in rural and urban areas, respectively.

(2) The prediction of population

The population prediction to calculate the EF should mainly take into account the birth, mortality, immigration and emigration of people and the conversion of rural and urban population. All the above factors can influence the numbers of rural and urban population and per capita EF and total EF sequentially. Figure 2 shows the diagram of population structure and possible conversions.

Currently the prediction of population in a certain region is estimated by population developing process models. For example, the continuous population development mode is described by partial differential equations, and its discrete model is described by difference equations, while the random model of population development is modeled by random process equations, and the dynamic model is established by system dynamics method, and so on. In this paper, the discrete population developing model (Ferng, 2001) is adopted and the prediction equations are:

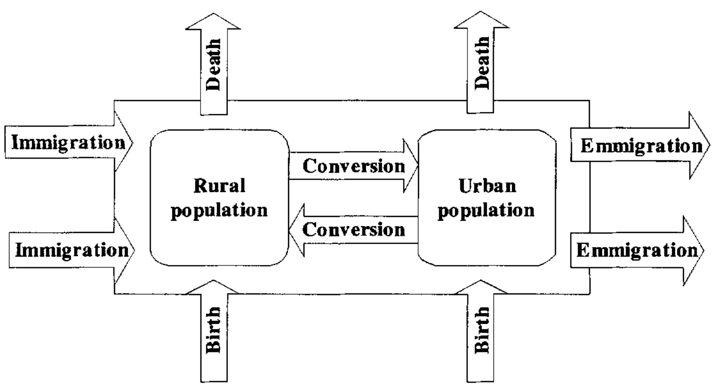

Figure 2 Change of population and its influencing factors

$$u_{00}(t) = u_{00}(t - 1)(1 - E_0) \quad (9)$$
$$u_i(t) = u_i(t - 1)(1 - E_i) \quad (10)$$
$$u_w = 1 \quad (11)$$
$$x_0(t) = [1 - u_{00}(t)]\beta(t)\sum_{i=r_1}^{r_2} k_i(t - 1)h_i(t)x_i(t - 1) \quad (12)$$
$$x_i(t) = [1 - u_{i-1}(t) + f_{i-1}(t)]x_{i-1}(t - 1) \quad (13)$$
$$x_i(0) = x_{io} \quad (14)$$

where $x_i(t)$, $k_i(t)$, $h_i(t)$, $u_i(t)$ and $f_i(t)$ are the number of population, female ratio, bearing probability, mortality probability and population migration ratio of that the age is i in prediction time t; $\beta(t)$ is the sum of bearing probability in prediction phase $\beta(t)$; $u_{00}(t)$ is mortality probability of newborn in prediction phase $\beta(t)$; x_{i0} is the number of the i-th age population; r_1 and r_2 are respectively the upper and lower limits of child-bearing female age; w is the highest and lowest age that people can live; E_0 and $E_i(t)$ are respectively attenuation ratio of death probability $u_{00}(t)$ and $u_i(t)$.

Based on the above method, we employed the China Population Statistical data from 1990 to 2000 and the Gansu Province Population Census Statistics in 2000 to predict population. Per capita EF of the study area is calculated from the total EF, the EF and population of rural and urban areas, and the result is 1.9762 ha•cap^{-1}.

4.3.2 The prediction of the EC The prediction of the EC is the prediction of all kinds of bio-productive land area in the study area. This paper uses Cellular Automata (CA) (Zhou *et al.*, 1999), a discrete dynamic system in time and space and composed of a series of rules that are constituted by models, to predict the conversion of land use types. The prediction process is described as follows:

(1) The calculation of land use transformation matrix: First, translating the land use vector data in 1995 and 2000 of Hexi Corridor into the 100 m × 100 m grid data. In the process of converting vector to grid data, the built-up land and water body have been taken into account especially, and the total area of any kind of land use is invariable and the conversion error is less than 1%. Using map algebra technology to calculate the land use grid data in 1995 and 2000, we obtain the land use change maps and the land use change transformation matrices of every county in Hexi Corridor from 1995 to 2000.

(2) The appraisement of land use suitability: data from meteorological stations in Hexi Corridor are interpolated in space to create the precipitation and accumulative temperature (greater than or equal to 10 ℃) vector data, and the contour data are used to create the slope vector data. All vector data, including the precipitation and cumulative temperature vector data, the slope vector data, the soil type and soil texture data, the relief data, and the water resource data, are translated into the 100 m × 100 m grid data. In this paper, based upon the principle of selecting the land suitability appraisement factors, soil, climate and relief elements are selected. Furthermore, the present status of land use is also selected as an important element. The soil element covers two factors: soil type and texture; and the climate element includes precipitation and accumulative temperature; while the relief element contains water resource, relief type and slope. We employed the empirical exponential sum method to estimate land suitability based on selected factors. To use this method, a weight is assigned to each factor according to their contribution to the land use suitability, then endow every land use unit with land use score for every factor. Also we adopted map algebra technique to superimpose layers and obtained the land use score of every unit.

(3) The simulation of land use type conversion. Using the land use transformation matrices from 1995 to 2000 and a series of maps of land use appraisement results, we employed the CA-MARKOV module of the Idrisi to simulate land use. In the simulation process, allowing for the rule of policy and economy impact, we adjusted the model parameter and obtained the land use simulation result in 2005. Finally, the area of all kinds of land use is obtained. The total EC

of every county and the study area is obtained in this table that is calculated by multiplying the area of all kinds of land use by the equivalence and yield factors and deducting 12% of the productive land area for protecting biodiversity. The total EC is divided by the total number of population to obtain per capita EC in 2005 with a value of 1.2833 ha•cap^{-1}.

4.4 The analysis of result

Figures 3 and 4 show the per capita and total ecological deficit status of every county in Hexi Corridor after calculating and rearranging their EF and EC from 1995 to 2005.

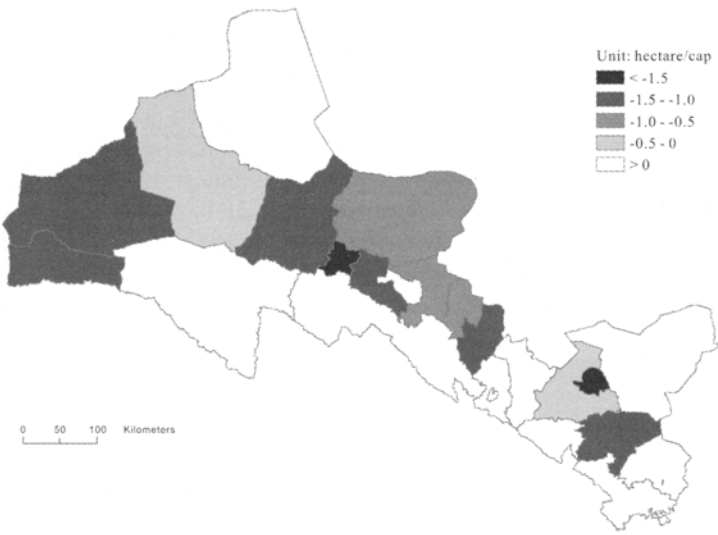

Figure 3 Ecological deficit status per capita of every county in Hexi Corridor

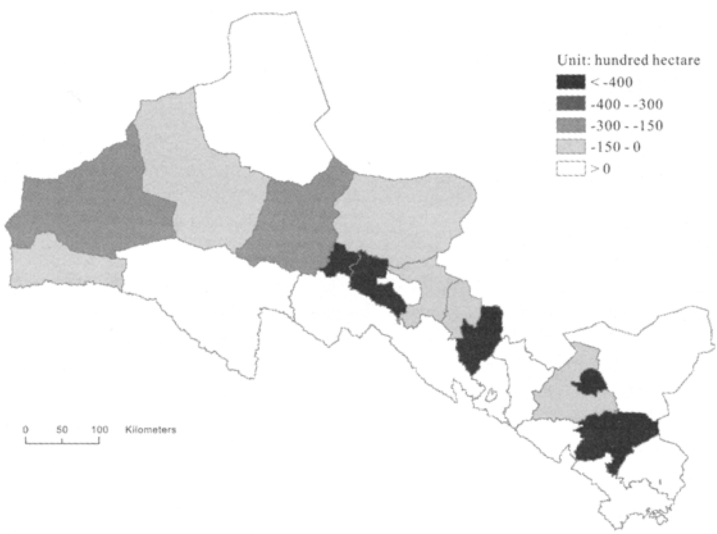

Figure 4 Total ecological deficit status of every county in Hexi Corridor

Based upon the above calculation and analysis, the following conclusions can be drawn.

(1) The counties' EC is greater than the EF in the eastern Hexi Corridor or the northern Qilian Mountains, which indicates they are in the state of ecological surplus. The counties' EC in the western Hexi Corridor, the central flat corridor zone, or nearby the Inner Mongolia Autonomous Region is smaller than the EF, indicating they are in the state of ecological deficit. The reason for such a distribution pattern is the relatively high precipitation is and the relatively low percentage of unused land and desert in the eastern Hexi Corridor and the northern Qilian Mountains. However, as the corridor zone is densely populated with relatively low precipitation in counties nearby Inner Mongolia, land desertification is serious.

(2) Every county's EF is going up in Hexi Corridor from 1995 to 2005 continually and the reasons are due to the increase of population and expansion of bio-productive land area resulting from rise of consumption levels. A majority of counties' EC ascended from 1995 to 2000 because of the increase of farmland following land reclamation. A majority of the counties' EC will descend from 2000 to 2005 because of the policy of converting farmland into forest or grassland. In addition, the constant decrease of water area is another important reason.

5 Conclusions

(1) In this paper, we adopt the down-to-up method to calculate the EC. Comparing the result with that of the EC calculated by from-up-to-down method about Zhangye County in related documentation (Zhou *et al.*, 1999), we find the results are basically consistent.

(2) We employ the remote sensing image interpreting method to acknowledge area of all kinds of land use to calculate the EC. It is of the character of accuracy and speediness. The research indicates that the method employing RS and GIS to calculate EC is feasible.

(3) We bring forward a suit of methods that predict the EF and the EC. In the process of prediction of EF, we predicted the future EF by combining consumption model with population model. While in the course of prediction of EC, we predict the future land use structure by GeoCA to calculate the future EC.

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