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An ecosystem service valuation of land use change in Taiyuan City, China

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ABSTRACT

Urban sprawl and a policy of converting farmland to woodland and grassland in the fragile ecological environments of the Loess Plateau of China can cause complex land use changes that significantly affect ecosystem services and functions. This study investigated changes in ecosystem services in response to land use changes caused primarily by human activities in Taiyuan City, the capital of Shanxi Province. Our aim was to provide guidance for sustainable urban development in fragile ecological environments undergoing rapid urbanization. We used remote sensing to evaluate land use changes, and applied a fast method for evaluating ecological service values at two points in time: 1990 and 2005. The ecosystem services value dropped from 743.53×10^6 yuan (1990) to 723.45×10^6 yuan (2005), mostly because farmland and grassland decreased. Over 95% of the total service value was attributable to woodland and farmland. Soil formation and protection, and water supply were the two largest service functions, contributing about 32% of the total service value. The results suggest that future land use planning should control the encroachment of urban areas on farmland, grassland, and woodland, and continue the policy of converting poor farmland to woodland and grassland.

1. Introduction

The valuation of ecosystem services is a topic of current concern in ecological economics research. Daily (1997) defines ecosystem services as the conditions and processes through which natural ecosystems, and the species they comprise, sustain and fulfill human life. Costanza et al. (1997a,b) define such services as goods and services that contribute to human welfare and are provided directly and indirectly by ecosystems. The growing body of literature on the valuation of ecosystem services includes studies on the value generated by ecosystems within urban areas (Bolund and Hunhammar, 1999); investigations into changes in ecosystem services value (*ESV*) in response to land use changes during urbanization (Kreuter et al., 2001; Li et al., 2010b); and studies on the impact of land use change on the provision of ecosystem services in tropical montane cloud forests (Martínez et al., 2009). Other studies have focused on how land use changes are coupled to ecosystem services (Metzger et al., 2006; Collard and Zammit, 2006; Yoshida et al., 2010) and how changes in the value of ecosystem services can be estimated (Chen et al., 2009; Li and Ren, 2008). In each of these studies, researchers have obtained insights that can provide important guidance for land managers.

Costanza et al. (1997a,b) classified the global biosphere into 16 ecosystems and 17 service functions, and then estimated the *ESV* of each, but their results have been severely criticized by many researchers (e.g. Serafy, 1998; Heal, 2000; Wilson and Howarth, 2002) due to the underestimation on *ESV* of farmland and the overestimation on *ESV* of wetland, and so on. Based on the survey on 200 Chinese ecologists, Xie et al. (2003) improved the valuation method of *ESV* mainly included the merging of some ecosystem service functions suggested by Costanza et al. (1997a,b) and extraction the equivalent weighting factors for ecosystem services per hectare for terrestrial ecosystems in China. Combined with land use data, the equivalent weighting factors have been used widely to evaluate the *ESV* in some terrains (e.g. Wang et al., 2004; Li et al., 2010a), cities (e.g. Li et al., 2010b), and watersheds (e.g. Zhao et al., 2010) of China. Their results suggest that land use type can be a proxy for ecosystem services by matching the land use types to equivalent biomes, thereby facilitating the valuation of ecosystem services for large areas using remote-sensing data.

Our study focused on Taiyuan City, a fast-growing heavy industrial city in China's eastern Loess Plateau. Dramatic changes in land use have occurred here in recent decades as a result of urban sprawl and a policy of returning farmland to woodland and grassland. These complex land use changes are likely to significantly affect ecosystem services and functions. The evaluation method mentioned above was applied to the object of our study, in order to estimate changes in *ESV* resulting from land use changes in Taiyuan City. Based on the estimated results, this paper attempts

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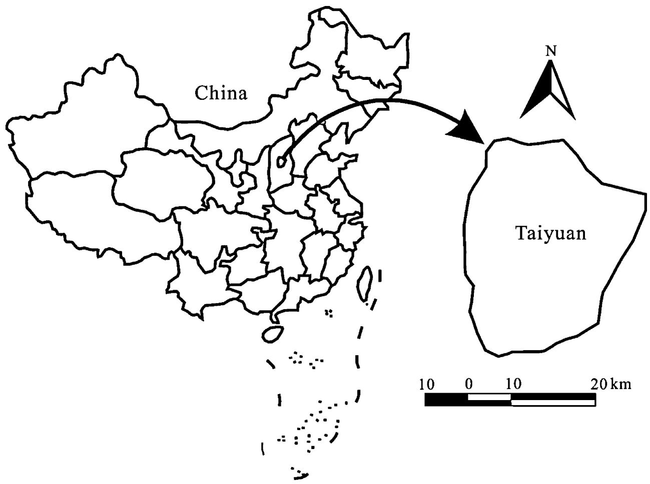

Fig. 1. Location of the study area.

to provide useful information and advice to support sustainable regional development policies.

2. Methods

2.1. Study site

Taiyuan City (lat. 32°20′N–34°08′N, long. 101°30′E–103°30′E, elevation 800 m above mean sea level), the capital of Shanxi Province, lies in the fragile ecological environment of the eastern Loess Plateau (Fig. 1). Covering a total area of 14,770 ha. Taiyuan City has a continental monsoon climate with a mean annual temperature of about 8 °C, annual rainfall of approximately 450 mm, and annual evaporation of 1045 mm over the last 40 years (Ma et al., 2011). Similar to other Chinese cities, Taiyuan City has experienced rapid urbanization and economic development. The GDP of Taiyuan City increased from 9.39×10^9 yuan in 1990 to 64.31×10^9 yuan in 2005. Rapid urban sprawl and a policy of converting farmland to woodlands and grasslands have resulted in complex land use changes that are more obvious in Taiyuan City than in other Chinese cities. This makes Taiyuan City an appropriate case study for assessing the changes in ecosystem services.

2.2. Data collection and land use classification

The data used to estimate changes in the sizes of various ecosystems were extracted from two cloud-free thematic mapper images obtained in 1990 and 2005, and one cloud-free enhanced thematic mapper image obtained in 2000. Although these satellite images were pre-georeferenced, they could not be compared directly because they used inconsistent coordinate reference systems and resolutions. We used a three-step image preparation procedure (Zhao et al., 2004) to reduce potential position errors among the three data sets: (1) we identified the *X* and *Y* coordinates of pairs of points that represent prominent features on both the 2000 enhanced thematic mapper image and a 1:50,000 topographic map of Taiyuan City; (2) with the topographic map as the georeferenced standard, we used GEOREFERENCING and RESAMPLING modules of IDRISI Release 2 software (Clark Labs, Worcester, MA) together to resample the 2000 enhanced thematic mapper data set into a Universal Transverse Mercator coordinate system; and (3) with the geo-rectified 2000 data from step 2 as the master data set, we resampled and rectified the 1990 and 2005 raw images using the step 2 procedure. An average root mean square error of less than 0.5 was achieved in steps 2 and 3 for all images, and the pixel size was retained at 30 m × 30 m. We used ArcView GIS software version 3.3 (ESRI, Redlands, CA) to consolidate and analyze our land use data. Taiyuan City includes all six land classification types listed in the resource and environment database established by the Chinese Academy of Sciences (farmland, woodland, grassland, water body, construction land, and unused land) (Table 1; Fig. S1, Supplementary information).

Table 1
Definition of land use type in Taiyuan City.

Type	Definition
Farmland	Paddy field, glebe field, irrigable land and vegetable field
Woodland	Arbor, bush forest and protection forest along the roads, railways
Grassland	Natural grassland and manmade grassland
Water body	Rivers, reservoirs fishery and lakes
Construction land	Land used for industrial, commercial, residential, transportation
Unused land	Lands unused or difficult for using

2.3. Dynamic information on land use

The dynamic information on land use during the 15-year period was calculated using the map algebra in ArcView GIS software version 3.3 (ESRI, Redlands, CA). According to the principles of map algebra, we can calculate any two periods of land use type figure (Yoshida et al., 2010). Using this method we obtained a transition matrix that reflects the quantitative relationship between different land use types in the study area.

2.4. Assignment of ESV

The equivalent weighting factors listed in Table 2 can be applied to different regions across China by localizing the average natural food production (Xie et al., 2003). The factor for the economic value of average natural food production of farmland per hectare per year was set at 1.0. All other coefficients were adjusted on the

Table 2
Equivalent weighting of ecosystem services per hectare of terrestrial ecosystems in China.[a]

	Farmland	Forest	Grassland	Wetland	Water body	Barren land
Gas regulation	0.50	3.50	0.80	1.80	0	0
Climate regulation	0.89	2.70	0.90	17.10	0.46	0
Water supply	0.60	3.20	0.80	15.50	20.40	0.03
Soil formation and protection	1.46	3.90	1.95	1.71	0.01	0.02
Waste treatment	1.64	1.31	1.31	18.18	18.20	0.01
Biodiversity protection	0.71	3.26	1.09	2.50	2.49	0.34
Food production	1.00	0.10	0.30	0.30	0.10	0.01
Raw material	0.10	2.60	0.05	0.07	0.01	0
Recreation and culture	0.01	1.28	0.04	5.55	4.34	0.01
Total	6.91	21.85	7.24	62.71	46.01	0.42

[a] From Xie et al. (2003).

Table 3
ESV (yuan ha^{-1} yr^{-1}) of different land use types in Taiyuan City.

	Farmland	Woodland	Grassland	Water body	Unused land	Construction land
Gas regulation	210.26	1471.79	336.41	0.00	0.00	0.00
Climate regulation	374.25	1135.38	378.46	193.43	0.00	0.00
Water supply	252.31	1345.63	336.41	8578.40	12.62	0.00
Soil formation and protection	613.94	1639.99	819.99	4.21	8.41	0.00
Waste treatment	689.64	550.87	550.87	7653.28	4.21	0.00
Biodiversity protection	298.56	1370.86	458.36	1047.07	142.97	0.00
Food production	420.51	42.05	126.15	42.05	4.21	0.00
Raw material	42.05	1093.33	21.03	4.21	0.00	0.00
Recreation and culture	4.21	538.25	16.82	1825.01	4.21	0.00
Total	2905.72	9188.14	3044.49	19,347.67	176.61	0.00

basis of this factor. In general, the proposed natural food production is 1/7 of the actual food production. From 1990 to 2005, the average actual food production from Taiyuan City farmland was 2453 kg ha^{-1}; the average 2005 price for grain was 1.20 yuan kg^{-1}. Applying the ecosystem service coefficient of 1.0 yields an ecosystem value of 420.51 yuan ha^{-1} ($1.0 \times 2453 \times 1.20/7$).

The *ESV* of each land use type in Taiyuan City per unit area was then assigned, based on the nearest equivalent ecosystems suggested by Xie et al. (2003) (Table 3). For example, woodland equates to forest, and unused land equates to barren land; only very small wetlands are distributed in areas along both sides of the rivers in Taiyuan City, and identifying them in remote sensing images is very difficult, so wetlands are not included in the land use types of the city. Although the biomes we used as proxies are not perfect matches with land use types every case (Kreuter et al., 2001), they are related (Li et al., 2010b).

2.5. Calculation of ESV

After we determined the *ESV* per unit area for each land use type, we determined the service value for each land use type, each service function, and for the total *ESV* as follows:

$$ESV_k = A_k \times VC_k \quad (1)$$

$$ESV_t = \sum_k A_k \times VC_k \quad (2)$$

$$ESV_f = \sum_k A_k \times VC_{kf} \quad (3)$$

where ESV_k, ESV_f, and ESV_t refer to the *ESV* for land use type *k*, service function *f*, and the total ecosystem, respectively; A_k is the area (ha) for land use type *k*; VC_k is the value coefficient (yuan ha^{-1} yr^{-1}) for land use type *k*; and VC_{kf} is the value coefficient (yuan ha^{-1} yr^{-1}) for land use type *k* with ecosystem service function type *f*.

Since the biomes we have used as proxies are not perfect matches with land use types (as mentioned above, see Section 2.4) and since there are uncertainties in the value coefficients, an additional sensitivity analysis is needed to determine the percentage change in *ESV* for a given percentage change in the value coefficient. In each analysis, we calculated a coefficient of sensitivity (*CS*) using the standard economic concept of elasticity, as follows (Kreuter et al., 2001):

$$CS = \frac{(ESV_j - ESV_i)/ESV_i}{(VC_{jk} - VC_{ik})/VC_{ik}} \quad (4)$$

where *i* and *j* represent the initial and adjusted values, respectively. If $CS > 1$, then the estimated ecosystem value is elastic with respect to that coefficient and it is important to accurately define *VC*; but if $CS < 1$, then the estimated ecosystem value is considered to be inelastic and the results of the *ESV* calculations will be reliable even if the *VC* value has relatively low accuracy. The greater the proportional change in *ESV* relative to the proportional change in the valuation coefficient, the more critical it is to use an accurate ecosystem value coefficient (Kreuter et al., 2001). The sensitivity analysis method has been used widely in previous studies (e.g. Li et al., 2010a,b).

3. Results

3.1. Changes in land use

Table 4 summarizes the land use changes in Taiyuan City between 1990 and 2005. Farmland and woodland were the two largest land use types in the study area in both 1990 and 2005. During the study period, the areas of woodland, water body, construction land, and unused land increased, while the areas of farmland and grassland decreased.

The transition matrix of land use types in Taiyuan City from 1990 to 2005 is shown in Table 5. We can conclude from Table 5 that most of the lost farmland that was converted into construction land, woodland, and grassland, whereas the lost grassland was converted primarily into farmland, construction land, and woodland. This was a combined result of urban sprawl, the policy of returning farmland to woodland and grassland, and grassland reclamation.

3.2. Changes in ESV

The *ESV* for each land use type and the total value for the two study years (1990 and 2005) were calculated using the value coefficients (Table 3) and the area covered by each land use type (Table 4).

Table 4
Taiyuan City land use patterns in 1990 and 2005.

Land use type	1990		2005		Change (1990–2005)	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Farmland	62,617.9	42.40	54,551.6	36.94	−8066.3	−12.88
Woodland	57,095.4	38.66	58,358.1	39.52	1262.7	2.21
Grassland	8029.0	5.44	3664.8	2.48	−4364.2	−54.36
Water body	646.6	0.44	906.2	0.61	259.6	40.15
Construction land	19,162.9	12.98	29,935.9	20.27	10,773.0	56.22
Unused land	125.1	0.08	260.3	0.18	135.2	108.07
Total	147,676.9	100.00	147,676.9	100.00		

Table 5
Transferring matrix (ha) for land use type in Taiyuan City from 1990 to 2005.

Land use type in 1990	Land use type in 2005					
	Farmland	Woodland	Grassland	Water body	Build up	Unused land
Farmland	41,703.3	9029.7	2160.3	175.4	9447.7	101.5
Woodland	8719.7	46,555.6	409.3	53.9	1324.7	32.2
Grassland	2696.4	2108.5	809.9	88.9	2249.9	75.4
Water body	73.9	3.5	1.2	493.0	75.0	0.0
Construction land	1329.0	642.2	274.0	85.7	16,811.0	21.0
Unused land	29.3	18.6	10.1	9.3	27.6	30.2

Table 6
Total *ESV* for each land use type, Taiyuan City in 1990 and 2005.

Land use type	*ESV* ($\times 10^6$ yuan yr^{-1})		Change (1990–2005)[a]	
	1990	2005	$\times 10^6$ yuan	%
Farmland	181.95	158.51	−23.44	−12.88
Woodland	524.60	536.20	11.60	2.21
Grassland	24.44	11.16	−13.29	−54.36
Water body	12.51	17.53	5.02	40.15
Unused land	0.02	0.05	0.02	108.07
Construction land	0	0	0	0
Total	743.53	723.45	−20.08	−2.70

[a] Positive and negative values represent increases and decreases, respectively.

Table 8
Percentage change in estimated total *ESV* and coefficient of sensitivity (*CS*) resulting from a 50% adjustment in ecosystem valuation coefficients (*VC*) in Taiyuan City.

Change in valuation coefficient	1990		2005	
	%	*CS*	%	*CS*
Farmland VC ± 50%	±12.24	±0.2447	±10.96	±0.2191
Woodland VC ± 50%	±35.28	±0.7056	±37.06	±0.7412
Grassland VC ± 50%	±1.64	±0.0329	±0.77	±0.0154
Water body VC ± 50%	±0.84	±0.0168	±1.21	±0.0242
Unused land VC ± 50%	±0.00	±0.0000	±0.00	±0.0001
Construction land VC ± 50%	±0.00	±0.0000	±0.00	±0.0000

The total *ESV* for Taiyuan City decreased approximately 2.7% over the study period (Table 6), primarily because of decreases in farmland and grassland. Although the *ESV* of other land uses increased, such increases were too small to offset the decreases.

Because woodland has the highest value coefficient (Table 3) and covers a large area (Table 4), the *ESV* of woodland is the highest of the six land use types, accounting for about 72% of the total value. Farmland also generates a high service value because of its large area; the combined *ESV* for woodland and farmland accounted for over 95% of the total *ESV*. Although the water body value coefficient is the highest of all land uses, water bodies cover a small area in Taiyuan City, thus this land use is associated with a very low service value. The *ESV* for grassland is also low for the same reason.

The values of individual ecosystem functions (ESV_f) are shown in Table 7. In general, the changes in the contribution of each ecosystem function to the total *ESV* are small. Soil formation and protection contribute most to the overall *ESV*, followed by water supply. This is likely a result of the ability of woodland – the largest land use – to form and protect soil.

3.3. Ecosystem sensitivity analysis

For the results of our analysis to be reliable, the sensitivity of *ESV* to changes in the value coefficients must be relatively low ($CS < 1$ in Eq. (4)). The percentage change in the estimated total *ESV* and the corresponding *CS* that results from a 50% adjustment in the service value coefficient indicate that total *ESV* is relatively inelastic with respect to changes in the value coefficients (Table 8). *CS* is highest for woodland (0.74) because of the large area and high value coefficient for this land use type. Overall, the sensitivity analysis indicates that our estimates for the study area are robust, despite uncertainties in the value coefficients.

4. Discussion

The method we used to estimate *ESV* was proposed by Costanza et al. (1997a,b), and modified by Xie et al. (2003) to account for Chinese conditions, and derives *ESV* by multiplying the area of a given land use type by the corresponding ecosystem value coefficient. However, as discussed by Limburg et al. (2002) and Turner et al. (2003), the estimates produced using this method have low resolution, high variation, and high uncertainty because of the complex, dynamic, and nonlinear properties of ecosystems. In addition, there are limitations on the economic valuation of land use types (Costanza et al., 1997b), and problems including double-counting and scales (Konarska et al., 2002; Turner et al., 2003; Hein et al., 2006).

Land use is used as a proxy measure of ecosystem services. However, the biomes used as proxies are not perfect matches with land use types in every case (Kreuter et al., 2001). In addition, the accuracy of the modified value coefficients (Table 3) is doubtful because of ecosystem heterogeneity. For instance, the proposed

Table 7
Value of ecosystem service functions (ESV_f) for Taiyuan City in 1990 and 2005.

	1990		2005	
	ESV_f (10^6 yuan yr^{-1})	%	ESV_f (10^6 yuan yr^{-1})	%
Gas regulation	99.90	13.44	98.59	13.63
Climate regulation	91.42	12.30	88.24	12.20
Water supply	100.88	13.57	101.30	14.00
Soil formation and protection	138.68	18.65	132.20	18.27
Waste treatment	84.01	11.30	78.72	10.88
Biodiversity protection	101.34	13.63	98.95	13.68
Food production	29.77	4.00	25.89	3.58
Raw material	65.23	8.77	66.18	9.15
Recreation and culture	32.31	4.35	33.36	4.61
Total	743.53	100.00	723.45	100.00

value coefficient of construction land is zero, neglecting negative effects of pollution (e.g. air pollution, water pollution, waste pollution) which may produce a negative value. Multiplying the area of land use type by the ecosystem value coefficient with uncertainties will therefore produce only rough estimates of *ESV* with a potentially high level of uncertainty.

The estimation of *ESV* based on land use data has been used successfully in other case studies (e.g. Yoshida et al., 2010; Li et al., 2010a,b). In some studies, other methods (e.g. indirect market evaluation) were used to calculate value coefficients. Although different valuation methods may lead to different estimated values, leading to criticism of the ecosystem service valuation approach, it is important to remember that accurately calculating coefficients is less critical for time series analyses than for cross-sectional analyses, because these coefficients tend to affect estimates of directional change less than they affect estimates of the magnitude of ecosystem values at specific points in time (Li et al., 2010a,b). Since our study focused on changes in *ESV* over time, the results are credible, particularly in qualitative terms. In addition, our sensitivity analysis indicated that the total *ESV* that we estimated for the study area were relatively inelastic with respect to the value coefficients, and that our estimates were robust despite uncertainties in the value coefficients. By calculating the *ESV* in 1990 and 2005 and analyzing changes across this time period, uncertainties and errors would be reduced or offset.

Economic growth often seems to conflict with ecological protection. Although the ecological and economical characteristics and the techniques of evaluation varied, the estimated results in Taiyuan City and other cities of China consistently showed that ecosystem services and functions tend to decline under current patterns of urban economic development (Wu et al., 2006; Yu et al., 2005). From 1990 to 2005, Taiyuan City's GDP increased by 584.88% (base on constant currency), while total *ESV* decreased by 2.70%. Although the decline in *ESV* was relatively low compared to economic growth, which was still worth attention because the *ESV* per hectare in Taiyuan City (5034.84 yuan ha^{-1} in 1990) was under the Chinese average (5843.59 yuan ha^{-1} for terrestrial ecosystems in 1994) (Chen and Zhang, 2000). Expressed as a multiple of GDP, Taiyuan City's *ESV* decreased by about 90% (=[8.0% − 0.8%]/8.0%) since 1990. This is a signal to regional planners that they must focus more on sustainable development and ecological protection in Taiyuan City due to its fragile ecological environment, so as to maintain a balance between economic development and ecosystem health in the future.

5. Conclusions

By analyzing and discussing the changes in *ESV* based on land use type in Taiyuan City from 1990 and 2005, we reached two primary conclusions. First, the total *ESV* for Taiyuan City decreased from 743.53×10^6 yuan in 1990 to 723.45×10^6 yuan in 2005, due mainly to the decreases in farmland and grassland. Woodland produced the largest proportion of the total *ESV* (about 74%), and combined woodland and farmland accounted for over 95% of the total *ESV*, indicating that the two land use types play major roles in providing ecosystem services. Second, soil formation and protection and water supply were the top two ecological functions, accounting for about 32% of the total. For Taiyuan City, sustainable development is critical due to its fragile ecological environment. A compromise between economic development and ecological protection must be reached. It is suggested that a reasonable land use plan should be made, with emphasis on controlling construction land encroachment (residential, commercial, industrial) on farmland, grassland, and woodland. Also, Taiyuan City should continue to implement the policy of returning farmland to woodland and grassland in areas that are not suitable for cultivation.

Our results suggest that land use type can be a proxy for ecosystem services by matching the land use types to equivalent biomes, thereby facilitating the valuation of ecosystem services for large areas using remote-sensing data. Because the reliability of the resulting estimates depends on the accuracy of value coefficients, future research should focus on methods that can calculate these coefficients more accurately. However, for time-series analysis such as we undertook in this study, our sensitivity analysis suggests that useful results are possible despite relatively imprecise coefficients.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2011.11.017.

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