Modeling hydrological ecosystem services and tradeoffs: a case study in Baiyangdian watershed, China

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Abstract Policy makers and scientists consider that land use strategies are designed to provide direct benefits to people by protecting vital ecosystem services. However, due to lack of information and evaluation methods, there is no effective and systematic tool for assessing tradeoffs between direct human benefits and ecosystem services. Land use changes influence ecosystem properties, processes and components, which are the basis for providing services. Five alternative land use scenarios (no conversion of agricultural lands, no urban expansion, agricultural expansion, forestry expansion, and riparian reforestation) were modeled for the Baiyangdian watershed, China, a densely populated, highly modified watershed with serious water shortage and pollution problems. The model InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is designed to inform decisions about natural resource management, with an aim to align economic forces with conservation. Three ecosystem services (agricultural production, hydropower production, and water quality) were modeled to balance direct benefits and hydrological ecosystem services using InVEST. The results showed that: hydropower production was the greatest in the forestry expansion, but the lowest in agricultural expansion;

agricultural production was reduced the most in forestry expansion, while retained the most in riparian reforestation. Riparian reforestation also provided the highest N and P retention and lowest N and P exportation. Riparian reforestation was the optimal land use strategy, since it protected and enhanced the vital ecosystem services without undermining direct human benefits. This research presents an initial analytical framework for integrating direct human benefits and ecosystem services in policy planning and illustrates its application. Although there are important potential tradeoffs between ecosystem services, this systematic planning framework offers a means for identifying valuable synergies between conservation and development.

Keywords Ecosystem services · Tradeoffs · Scenarios · InVEST

Introduction

Ecosystem services are the benefits that humans derive from ecosystems, which include provisioning, regulatory, supporting and cultural services (Millennium Ecosystem Assessment 2003; de Groot et al. 2002; Egoh et al. 2009). The evaluation of ecosystem services is one of the common issues in ecological economics (Costanza et al. 1997; Daily et al. 2000). Better decisions regarding the sustainable use and management of ecosystem services are made by analyzing and quantifying the importance of ecosystems to human well-being (Chen et al. 2009).

With the rapid increase in human population and the over consumption of natural resources, the demands for ecosystem services often surpass their provisioning capacity (Vitousek et al. 1997; Bennett et al. 2005). Humans frequently enhance the production of some services at the

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expense of the others (Jackson et al. 2001; Zhang et al. 2010). Development has generated significant economic and social benefits, but these benefits have often come at high costs associated with the deterioration of natural capital and ecosystem services through processes such as soil erosion, reduced quantity and quality of fresh water, salinity, and biodiversity depletion (Tilman 1999). Ready access to market exchange results in managers of privately owned natural capital stocks preferentially producing marketed ecosystem services at the expense of non-market services. Over time, this results in the under-supply of the latter and the long-term deterioration of the natural capital stocks and ecosystem service flows (Lant et al. 2008; Yang et al. 2010). The Millennium Ecosystem Assessment (MA 2005) focused on services of different ecosystems, stressing their overall decline (Dolinar et al. 2010). Continuing ecosystem services loss urgently requires techniques to rapidly assess and monitor changes in ecosystem services (Balvanera et al. 2001; Menon and Bawa 1997; Margules and Pressey 2000; Ramesh et al. 1997; Stork and Samways 1995; Krishnaswamy et al. 2009).

When decision makers and scientists set out to explore the possible redesign of landscapes, often at different scales, they need information about their ecological function and how a change in the mix of land use will impact on tradeoffs between production needs and other human needs. If possible, tradeoffs should be quantified in terms of the sustainable delivery of ecosystem goods and services from resilient ecosystems and be matched to human well-being (Bennett et al. 2009; Yapp et al. 2010). To make better decisions, a systematic account of the relationships between ecosystem management and the generated ecosystem services is needed (de Groot et al. 2010). There are recent assessments of natural capital and ecosystem services (e.g., Blashke 2005; Haines-Young et al. 2006; Chan et al. 2006; Naidoo and Ricketts 2006; Gimona and Van der Horst 2007; Egoh et al. 2008; Meyer and Grabaum 2008; Grêt-Regamey et al. 2008; Naidoo et al. 2008; Raymond et al. 2009). However, they are not suitable for representing services at a single location or assessing the spatial and temporal services change. Dynamic visualization alternatives under different developing scenarios need to be explored to represent changing services in space and time (de Groot et al. 2010). Due to lack of original data and effective evaluation methods, there has been little research about tradeoffs between direct benefits and other vital ecosystem services. There are no effective and systematic methodologies for land use management that link ecosystem services.

This study focuses on the application of InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) (Tallis et al. 2008), a model developed to measure and evaluate ecosystem services under land management scenarios reflecting different priorities, illustrated through a case study of the Baiyangdian watershed, China. The

Baiyangdian watershed is a human-dominated watershed with serious water shortage and pollution problems, in which agricultural land accounts for nearly 37 % of the total area. The broad aim of this study is to provide guidance to organizations for better designing and promoting sustainable land management in Baiyangdian watershed. The methodology presented here demonstrates the impacts of contrasting hypothetical land use scenarios with different policy objectives on the delivery of ecosystem services, and the synergies and tradeoffs between them. Given this challenge, two questions are addressed:

- (1) How to map and assess ecosystem services across landscape scale?
- (2) How to manage tradeoffs of several ecosystem services in a watershed?

Study area and methods

Study area

The Baiyangdian watershed (Fig. 1) is located in the middle of the North China Plain and covers an area of 31,200 km². It has a complex topography with higher lands in the west and lower lands in the east. Mountainous areas are mainly covered with forest and grass, which account for 64 % of the total area; plain areas are mainly cropland. Forest, grass, and cropland account for 26.13, 26.74 and 36.57 % of the total area, respectively. According to the weather records from the past 50 years (from Baoding, Shijiazhuang, Wutaishan, Weixian, and Huailai weather stations within or adjacent to the watershed), the mean annual temperature is between 6.8 and 12.7 °C (the daily maximum value is 43.3 °C and the daily minimum value is −30.6 °C), the mean annual precipitation is 548 mm and the mean annual pan evaporation is 1,500–2,000 mm. The Baiyangdian watershed has a high population density, more than 448 people km^{−2}; compared to 45 people km^{−2} of the average population density worldwide. The area also suffers from extreme water shortage. The water availability per capita is 297 m³ (the annual average water availability is 3.12 billion m³). Due to natural conditions and human activities in recent years, river flow has decreased and is polluted with urban domestic sewage, industrial waste and agricultural pesticides and fertilizers, causing serious contamination. The environment of Baiyangdian watershed is undergoing serious threats.

Land use scenarios

Five alternative land use and land cover (LULC) scenarios were developed to examine the potential synergies of

Fig. 1 The Baiyangdian watershed

tradeoff in the delivery of ecosystem services among land uses. These were chosen to reflect the current situation and alternative uses under different policy options. Alternative scenarios were developed as follows.

Se1: No agricultural lands converted scenario

No conversion of agricultural lands between 1980 and 2007. Due to rapid urbanization and population growth, the urban area increased and agricultural lands decreased dramatically in this area.

Se2: No urban expansion scenario

All land use conversions to urban areas were reverted to their 1980 land use.

Se3: Agricultural expansion scenario

Based on a land suitability assessment of the Baiyangdian watershed, the most productive lands that were not in

agriculture as of 2007 were converted to agriculture by 2007, with the exception of urban areas and open water.

Se4: Forestry expansion scenario

Based on a land suitability assessment of the Baiyangdian watershed, all land most suitable for forestry that was not forested as of 2007 was converted to forestry. Urban areas, open water and the most highly productive agricultural lands were the only exceptions to this rule. These areas retained their actual LULC.

Se5: Riparian reforestation

In this scenario, a 50-m buffer zone was established on both sides along the river network considering local reality and the conversion costs. Due to lack of water resources infrastructure, farm land is often distributed along rivers for easy irrigation in the Baiyangdian watershed. The wider the buffer zone is selected, the more farm land will be converted to forest, which will increase the conversion costs. All lands in the buffer zone were placed into forestry.

Fig. 2 The observed data versus predicted data (Note that x -axis is observed value, while y -axis is predicted value. **a** water yield, 10^8 m³ per year; **b** N exportation, ton per year; **c** P exportation, ton per year.)

Table 1 The results of t test

	SD	t	Sig.
Water yield	0.376	0.197	0.853
N retention	5.31	0.307	0.774
P retention	0.596	0.293	0.784

Urban areas and open water in 1980 were the only exceptions to this rule. These areas retained their actual LULC.

InVEST description

InVEST uses land use and land management information along with environmental conditions as inputs into ecological production functions to generate spatially explicit predictions of ecosystem service supply. By varying land use or land management input and evaluating the output from InVEST, information can be provided to managers about the likely impacts of their choices on the joint provision and value of ecosystem services. This information can be used to compare alternative management options in terms of biophysical measures of services, the overall value of services generated, or disaggregated information about various stakeholders that may benefit or be harmed (Daily et al. 2009; Nelson et al. 2009). For this application,

hydropower, water quality (nitrogen and phosphorus), and agricultural production in each scenario were modeled. The assumptions and limitations of each module will be discussed in the following part.

Hydropower production

The InVEST Reservoir Hydropower model estimates the relative contributions of water from different parts of a landscape, offering insight into how changes in land use patterns affect annual surface water yield and hydropower production. This model has several limitations. First, the model assumes that all water produced in a watershed in excess of evapotranspiration arrives at the watershed outlet, without considering water capture by means other than primary human consumptive uses. Second, the model assumes that hydropower production and pricing remain constant over time. Third, this model is based on annual averages, which neglect extremes and do not consider the temporal dimensions of water supply and hydropower production. Fourth, the model does not consider sub-annual patterns of water delivery timing. Fifth, the model describes consumptive demand by LULC type. Finally, a single variable is used to represent multiple aspects of water resource allocation, which may misrepresent the complex distribution of water among used and over time (Tallis et al. 2008).

Table 2 Alternative LULC under different scenarios (ha)

	2007	Se1	Se2	Se3	Se4	Se5
Agriculture	1,011,720	1,103,470	1,176,190	1,480,830	910,610	992,125
Grassland	739,678	745,882	746,748	411,897	397,948	613,775
Open water	28,302	73,380	32,373	50,160	27,896	23,637
Urban area	258,783	118,999	81,729	205,103	256,754	249,493
Wasteland	4,983	4,218	5,051	1,417	3,312	4,772
Forestland	723,102	720,617	724,481	617,159	1,170,050	882,768

Table 3 Tradeoff of hydrological services under different scenarios

	Water yield (million m ³)	Retention		Exportation	
		N (million kg)	P (million kg)	N (million kg)	P (million kg)
2007	360.91	28.60	0.96	9.18	0.45
Se1	385.98	24.93	1.05	6.15	0.40
Se2	372.50	24.75	1.11	5.58	0.43
Se3	138.31	30.62	1.25	9.86	0.65
Se4	584.08	27.84	0.92	8.91	0.42
Se5	432.34	30.66	1.27	5.26	0.24

Fig. 3 Mapping hydropower productions in scenarios

Water quality

The InVEST water quality model evaluates the pollutant retention service provided by a landscape and highlights the

impacts of land use change on water quality when provided with alternative LULC scenarios. Although there are multiple potentially significant impairments of water quality, in this study we focused on nitrogen (N) and phosphorus (P).

Fig. 4 Mapping N and P retention in scenarios

This model has several assumptions. First, this model may be less applicable to locations where the hydrology is

determined by rainfall intensity; in areas where flashy rains are predominant and where infiltration excess runoff occurs. Second, the model can only assess one pollutant per run. Third, in some cases, the model may provide an inaccurate marginal cost for pollutant removal (Tallis et al. 2008).

Agricultural production

InVEST uses information on the observed relationships between soil quality and yields, observed yield trends, observed prices for agricultural produce, and agricultural production costs to estimate the annual net market returns of agricultural production. Combining expected yield with crop prices generates an estimate of revenue. Subtracting costs from revenues generates an estimate of economic returns from agricultural activity.

Model validation for water quality

Five actual measurement points were selected in this watershed. Each point has monitoring data of yearly water yield and water quality. Those on-site measured data were used to validate InVEST model. The graphs show the correlations between the observed and predicted data (Fig. 2). The t test accepts the null hypothesis at the default $\alpha = 0.05$ significance level (Table 1). Under the null hypothesis, there is no extreme difference between observed and predicted data, as indicated by the p value (0.853, 0.774 and 0.784, respectively), which is higher than α .

Results

Land use change

Table 2 shows the actual (2007) and the five alternative LULC scenarios. The area of agriculture was the greatest in Se3 (1,480,830 ha), and smallest in Se4. Se5 was the scenario most closely resembling the actual area of agriculture in 2007. Se3 had the smallest area of forested land, with 105,943 ha less forested area compared with 2007. Forested lands were greater than actual condition for both Se4 and Se5, but the difference for Se4 was 2.8 times that of Se5. Due to the expansion of agricultural and forest land, grasslands decreased dramatically both in Se3 and Se4. The urban area decreased dramatically in both Se1 and Se2.

Ecosystem service changes

Based on the water yield model, the amount of water used for hydropower was 360.91 million m^3 in 2007, and its value was 21.91 million dollars. Compared with 2007, hydropower production decreased in Se3 (by 13.51 million

Fig. 5 Changes to hydrological services under different scenarios compared to 2007

Fig. 6 Hydrological services change association with 1 % agricultural change (based on 2007 scenario)

dollars). Hydropower production increased with forestland expansion, with Se4 increasing by 13.55 million dollars and Se5 increasing by 4.34 million dollars (see Table 3; Fig. 3). As for water yield, Se4 and Se5 are better than Se1, Se2 and Se3. The water yield in Se4 and Se5 are 584.08, 432.34 million m³, and 385.98, 372.50, 138.31 million m³ in Se1, Se2, Se3, respectively.

The total N retention in 2007 was 28.60 million kg. Se5 had the highest N retention, with 30.66 million kg. Se3 was the second highest, with 30.62 million kg. Se2 had the least N retention, with 24.74 million kg. Compared with 2007, N retention decreased in Se1, Se4, and especially in Se2, while Se5 increased more than Se3. From the perspective of land use type, the highest N retention was caused by agriculture under all scenarios, followed by grassland and forestland. Compared to 2007, the amount of N retention in agriculture only increased for Se3, while it decreased dramatically in Se1. Conversely, the amount of N retention for forested lands increased for Se3, Se4 and Se5, with highest increasing for Se5 (see Table 3; Figs. 4, 5). This means Se5 can provide the highest N retention services throughout the whole scenarios.

The total P retention in 2007 was 0.96 million kg. Se5 had the highest P retention, with 1.27 million kg. Se3 was

the second highest, with 1.25 million kg, and Se4 the least, with 0.92 million kg. Compared with 2007, P retention only decreased in Se4; Se5 increased the most, by 0.31 million kg. Comparing land use types, the greatest P retention was caused by agriculture under all scenarios, followed by grassland and forestland. Compared to 2007, the amount of P retention increased for all scenarios except Se4; on the other hand, the amount of P retention in forest land increased for all scenarios, especially in Se5 (see Table 3; Figs. 5, 6). This means Se5 can provide the highest P retention services throughout the whole scenarios.

Discussion

The present study focuses on the management of ecosystems to protect the current human direct benefits without sacrificing hydrological ecosystem services. The direct income for local people is mainly from agriculture. In other words, the greater the area of agricultural land, the greater the direct benefit they will gain, to some extent. However, expansion of agriculture without planning can cause serious environmental problems. This research assessed the

Fig. 7 Mapping N and P retention changes in scenarios (based on 2007)

tradeoffs between direct benefits and hydrological ecosystem services and selected the best scenario.

Table 3 and Fig. 6 show the tradeoff among different ecosystem services for the five land use scenarios. Agricultural production for both Se1 and Se2 was similar to the

actual condition (2007). However, N and P retention was too low, resulting in high N and P exportation, which degraded the water quality downstream. Agricultural production was the highest for Se3 but its N and P exportation was the greatest too (N: 9.65 million kg and P: 0.65 million kg). Se4 yielded the highest hydropower production, but its agricultural production was only 1.41 billion units, and its N and P exportation was very high. In Se4, hydropower production increased but this was at the cost of agricultural production, which declined dramatically. This kind of land use strategy is not sustainable in the long run, since the unilateral pursuit of environmental protection and reforestation occurs largely at the expense of the local people's direct benefits. Se5 was also a forestland expansion strategy, but the result was very different. The increase in forested area for Se5 was far lower than that of Se4 (compared to 2007), but the N and P retention was greatest and the N and P exportation was lowest (Fig. 4). The direct human benefits decreased only slightly, and its hydropower production ranked second among all scenarios. This means that Se5 was the optimal land use management strategy, since it guarantees agricultural production while also increasing hydrological ecosystem services. Se5 also indicated the importance of riparian vegetation protection.

Conclusions

Most researchers only consider the single value of ecosystem services, without evaluating how the services are generated during different land use management strategies and without assessing how small land use changes would influence the services (Costanza et al. 1997). Such information might improve awareness of the value of natural ecosystems; however, it cannot provide a good basis for policy formulation and guidance. Water management in agriculture is a key component in solving some of the most pressing tradeoffs between an increase in agricultural production that can contribute to food security and economic growth on the one hand, and dealing with the losses of important ecosystem benefits that also sustain human well-being and livelihoods on the other (Gordon et al. 2010). In response to this complex challenge, using the InVEST model, three kinds of ecosystem services were analyzed under different land use scenarios.

Se5 was the optimal sustainable land use strategy, since it could gain the best social and environmental benefits. These results suggest that ecological regulation can insure local people direct benefits as well as improve other ecosystem services. Tradeoffs in this research cannot only help making reasonable ecosystem management strategies, but also assist natural resource managers in prioritizing areas where remnant vegetation should be retained or

rehabilitated (Fig. 7). With this information, adjacent landholders can improve their management and remnant vegetation through gaining the ecosystem service benefits, and further are able to profit from grant applications and incentives. The next step may be to find the most ecologically sensitive areas or priority areas for conservation. The methodology from this research can also be used to address these challenges.

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