Postprint: Trade-off Optimization of Ecosystem Services in the Wei River Basin

Authors: Chen Dengshuai, Li Jing, Yang Xiaonan, Liu Yan

Date: 2018-05-18T00:00:00+00:00

Abstract

Investigating the complex relationships among ecosystem services and between ecosystem services and land use types, and conducting ecosystem service-oriented land use optimization, is of great significance for achieving coordinated and sustainable development of socio-economy and ecological protection. Taking the Guanzhong-Tianshui Economic Zone section of the Wei River Basin (hereinafter referred to as the Guanzhong-Tianshui section) as the study area, this study estimated three ecosystem services—biodiversity, carbon sequestration, and water yield—at the sub-watershed scale for the period 2000-2013, and quantitatively examined the trade-off and synergistic relationships among them. Furthermore, the CA-Markov model was employed to predict land use change scenarios for 2050, based on which future ecosystem services were calculated and the Production Possibility Frontier (PPF) method was introduced to conduct trade-off and synergistic analysis, thereby exploring the optimal land use pattern under maximum ecosystem services for 2050. The results indicate: The total water yield in the study area showed an increasing trend from 2000 to 2013. The Qinling Mountains and Liupan Mountains regions exhibited higher total carbon sequestration and better biodiversity quality, whereas the Guanzhong Plain, with dense population and urban distribution, demonstrated poorer carbon sequestration capacity and generally higher degrees of habitat degradation. Carbon sequestration and biodiversity exhibited a synergistic relationship, while water yield versus biodiversity and water yield versus carbon sequestration both showed trade-off relationships. The optimal Pareto efficiency curve under ecosystem services for 2050 was delineated, and through further trade-off and synergistic analysis, the corresponding land use optimization map was obtained. Integrating ecosystem services and trade-off requirements into land decision-making and optimized management processes will facilitate achieving a win-win state for ecology, society, and economy in the study area.

Full Text

Trade-offs and Optimization Among Ecosystem Services in the Weihe River Basin

ACTA ECOLOGICA SINICA, Vol. 38, No. 9, May 2018
DOI: 10.5846/stxb201707011187

Authors: CHEN Dengshuai[1],[2],, *LI Jing*[1]*, YANG Xiaonan*[1]*, LIU Yan*[1]
[1]*School of Geography and Tourism, Shaanxi Normal University, Xi’ an 710119, China*
[2]*National Demonstration Center for Experimental Geography Education, Shaanxi Normal University, Xi’ an 710119, China*
Corresponding author. E-mail: lijing@snnuedu.cn

Abstract

Understanding the complex relationships between ecosystem services and land use types, and conducting ecosystem service-oriented land use optimization, are crucial for achieving coordinated and sustainable socioeconomic development and ecological protection. This study examines three key ecosystem services—biodiversity, carbon sequestration, and water yield—in the Guantian section of the Weihe River basin from 2000 to 2013 at the sub-basin scale. Using the CA-Markov model, we simulated land use change scenarios for 2050 and estimated future ecosystem services under these scenarios. We then introduced the Production Possibility Frontier (PPF) to generate optimal land use patterns for maximizing ecosystem services in 2050. The results indicate: (1) From 2000 to 2013, total water yield in the study area showed an increasing trend. Total carbon sequestration was relatively high in the Qinling and Liupan Mountains where biodiversity quality was also high, while the Guanzhong Plain region, with dense population and urban distribution, exhibited poor carbon sequestration capacity and generally high habitat degradation. (2) A synergistic relationship existed between carbon sequestration and biodiversity, whereas trade-offs were observed between water yield and biodiversity, as well as between water yield and carbon sequestration. (3) Optimal land use patterns for 2050 were generated based on the Pareto efficiency frontier between ecosystem services. Integrating ecosystem services and trade-off analyses into land system architecture and optimal management provides significant value for sustainable environmental and economic development in the study area.

Keywords: biodiversity; carbon sequestration; water yield; trade-off; scenario; optimization

1. Study Area and Data Sources

1.1 Study Area

The Weihe River is the largest tributary of the Yellow River, flowing primarily through Tianshui in Gansu Province and merging into the Yellow River at Tongguan County, Shaanxi Province. The river stretches 818 km with an average annual runoff volume characterized by significant interannual variation. The terrain features high elevation in the west and low elevation in the east, divisible into two parts: western loess hills and gullies, and the eastern Guanzhong Plain. The Qinling Mountains run east-west to the south, while the Liupan Mountains form a barrier to the north. Seasonal variation is pronounced, with autumn flows comprising 38%-40% of annual runoff.

The Guantian section (Guanzhong-Tianshui Economic Zone section) serves as Shaanxi Province' s administrative center and economic hub, encompassing Xi' an, Xianyang, Baoji, Weinan, the Yangling Demonstration Zone, and parts of Shangluo. This region exhibits high population density and urbanization levels. The Weihe River supports production, domestic water use, and ecological water supplementation for the economic zone. [Figure 1: see original paper] shows the location of the Guantian section in the Weihe River basin.

1.2 Data and Processing

This study utilized base geographic information data, land use data (2000, 2005, 2010, 2013), field sampling and survey data, and meteorological data for the Guantian section of the Weihe River basin. We collected 150 soil sample data points along routes encircling the study area. Soil organic carbon content was measured using the potassium dichromate oxidation external heating method [15] and validated against soil organic carbon content calculated from a carbon cycle model inversion, achieving a correlation coefficient of 0.7391. Land use type maps interpreted from remote sensing were verified and corrected using Google Earth imagery and field surveys.

---

2. Methods

2.1 Carbon Sequestration Estimation

Carbon sequestration in this study comprises above-ground and below-ground components. The above-ground component was estimated using Net Primary Productivity (NPP) calculated via the CASA (Carnegie-Ames-Stanford Approach) model:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t)$$

where x represents spatial location, t represents time, $APAR(x,t)$ denotes photosynthetically active radiation absorbed at location x in month t (MJ m ^{2} month ^{1}), and $\varepsilon(x,t)$ represents light use efficiency at pixel x in month t (gC/MJ). Each kilogram of dry matter corresponds to 1.63 kg of carbon.

The below-ground component focused on soil organic carbon, using an improved carbon cycle process model from Zhou et al. [17] to invert soil basal respiration. Regression analysis with soil survey data yielded the relationship between soil respiration and soil organic carbon content. The carbon cycle process model calculates:

$$A_{ij} = b \times T \times y$$

where A_{ij} represents soil basal respiration, b is a temperature-sensitive constant factor, T is temperature, and y is net primary productivity.

2.2 Biodiversity Estimation

We applied the biodiversity module of InVEST software to calculate habitat quality index, with results ranging from 0 to 1, where higher values indicate better habitat quality and biodiversity. The habitat quality calculation follows:

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right)$$

where Q_{xj} is the habitat quality of pixel x in land use type j, H_j is the habitat suitability of land use type j, D_{xj} is the habitat threat level for pixel x in land use type j, k is a scaling parameter, and z is a normalization parameter. The threat level D_{xj} is determined by:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r}\right) r_y \beta_x S_{jr}$$

where r_y is the threat factor, w_r is the weight of threat factor r, β_x is the accessibility level of pixel x, and S_{jr} is the sensitivity of land use type j to threat factor r.

2.3 Water Yield Estimation

Water yield service was calculated using the SWAT model' s water yield module [18] with a catchment area threshold of 15,000 hm^2. The formula is:

$$WYLD = SURQ + LATQ + GWQ - TLOSS - PA$$

where $WYLD$ is total water yield (mm), representing total water entering the main river channel during the time step; $SURQ$ is surface runoff contribution (mm); $LATQ$ is lateral flow contribution (mm); GWQ is groundwater contribution (mm); $TLOSS$ is channel transmission loss (mm); and PA is pond abstractions (mm).

Model accuracy was validated using measured runoff data from the Xianyang hydrological station. The calibration period (1990-1999) achieved $R^2 = 0.78$ and $NES = 0.71$, while the validation period (2000, 2005, 2010, 2013) showed good agreement with $R^2 = 0.73$, demonstrating the model' s strong applicability in the Weihe River basin. [Figure 2: see original paper] compares simulated and measured monthly runoff during calibration and validation.

2.4 Land Use Scenario Prediction

Based on historical land use transition patterns and future development plans, we constructed three land use development scenarios for 2050 using the CA-Markov model in IDRISI [19]:

1. **Development Scenario**: Prioritizes urbanization, converting farmland and sparse shrubland at urban edges to construction land.
2. **Conservation Scenario**: Restricts urban development, prioritizes ecological protection, implements returning farmland to forest/grassland on slopes >15°, and strictly limits industrial land encroachment on farmland.
3. **Planning Scenario**: Continues existing land use trends, referencing the Weihe River basin land use master plan to adjust future land type areas and distributions.

Different parameters and weights were assigned for driving and limiting factors (e.g., water systems) under each scenario.

2.5 Ecosystem Service Optimization

We applied the Production Possibility Frontier (PPF), also known as the Pareto frontier, to optimize future ecosystem services [20]. PPF represents the maximum possible output combination of products given fixed resources. Mathematically expressed as a curve, it reflects potential and excess—points below the curve indicate underutilized resources with optimization potential, points on the curve represent optimal allocation, and points beyond are unattainable.

To construct the Pareto efficiency curve between biodiversity and water yield: 1. Divide the biodiversity raster by the water yield raster to create a ratio layer 2. Sort cells by ratio in ascending order 3. Calculate cumulative sums of biodiversity quality and water yield along the sorted sequence 4. Plot these cumulative values to generate the Pareto efficiency curve

---

3. Results

3.1 Spatiotemporal Changes in Ecosystem Services

Using relevant models, we mapped water yield, carbon sequestration, and biodiversity in the Guantian section from 2000 to 2013. [Figure 4: see original paper] shows the spatial distribution.

Water Yield: Showed an increasing trend, with average sub-basin water yield of 110.847 mm in 2000, 247.91 mm in 2005, and 275.42 mm in 2013. The increase was primarily driven by higher precipitation and intense rainfall events. Spatially, downstream areas showed the highest yields, followed by midstream and upstream regions.

Carbon Sequestration: Spatial patterns remained relatively stable, with the highest average carbon sequestration (27.6 t/hm^2) in sub-basins of the Qinling Mountains (sub-basins 1-3) due to extensive forest cover. The Guanzhong Plain showed lower sequestration capacity. Local variations were influenced by precipitation changes and land use conversions.

Biodiversity: Habitat quality scores ranged from 0.29 to 0.73, declining overall from 2000 to 2013. The Qinling Mountains maintained high scores due to low ecological threat intensity and distance from disturbance factors. Guanzhong Plain scores were lower (0.29-0.45), reflecting habitat fragmentation and increased ecological vulnerability from urbanization. [Figure 3: see original paper] shows land use patterns for 2000, 2010, and 2050.

3.2 Correlations Between Ecosystem Services

Using R and Python programming, we analyzed correlations between ecosystem services at the sub-basin scale. [Figure 5: see original paper] visualizes these relationships through scatter plots and pie charts, where pie chart fill size represents correlation magnitude and color intensity represents value strength. Clockwise filling indicates positive correlation (pink for negative, blue for positive).

Carbon Sequestration vs. Biodiversity: Consistently positive correlation (synergy), with correlation coefficients of 0.63 (2000), 0.26 (2005), 0.78 (2010), and 0.13 (2013). When cumulative carbon sequestration increased by 50×10 t, biodiversity increased by 0.63×10 units, demonstrating mutual benefits.

Carbon Sequestration vs. Water Yield: Consistently negative correlation (trade-off), with coefficients of -0.45 (2000) and -0.08 (2005). The PPF curve shows increasing slope from right to left, indicating that gaining 50×10 t of carbon sequestration costs 204.7×10 m^3 of water yield initially, but 541.1×10 m^3 at higher levels—demonstrating varying opportunity costs.

Biodiversity vs. Water Yield: Negative correlation (trade-off), with the Pareto efficiency curve slope also increasing from right to left, showing similar trade-off dynamics.

[Figure 6: see original paper] illustrates the PPF between carbon sequestration, biodiversity, and water yield.

3.3 Optimal Ecosystem Service Allocation

We simulated 2050 land use scenarios and plotted the three ecosystem service combinations under each scenario. All points fell below the optimal Pareto frontier, indicating optimization potential.

Taking carbon sequestration and biodiversity as an example, the optimal Pareto frontier represents the best achievable ecosystem service combinations. To reach the frontier from current conditions, two extreme pathways exist: 1. **Vertical shift**: Increase biodiversity while maintaining carbon sequestration (moving to point b: 150, 2.16) 2. **Horizontal shift**: Increase carbon sequestration while maintaining biodiversity (moving to point d: 132, 1.88)

The corresponding optimal land use patterns show significant spatial differences. For instance, point b features 9.51×10 hm^2 forest and 1.02×10 hm^2 water area, while point d has 5.19×10 hm^2 forest and 1.01×10 hm^2 urban land. [Figure 8: see original paper] displays land use distributions under optimal Pareto frontier points. Any land use transformation moving service combinations closer to the frontier constitutes optimization.

4. Discussion

This study introduces the Production Possibility Frontier to quantitatively analyze dynamic trade-offs and synergies among carbon sequestration, biodiversity, and water yield. Python programming enables more intuitive visualization of these relationships beyond simple correlation analysis.

From a scientific perspective, the complex relationships between multiple ecosystem services and geographic environments require further investigation. Future research should explore driving mechanisms of dynamic changes in trade-off/synergy relationships and examine scale effects under spatial heterogeneity.

From a practical decision-making standpoint, land use/cover change is the primary driver altering ecosystem service relationships [23-24]. Our results show trade-offs between water yield and carbon sequestration. Notably, 2005 exhibited significant correlation changes due to a ~70 mm precipitation increase and marked land use changes: forest area decreased by 62,214 hm^2 while urban land increased by 18,504 hm^2. Reduced vegetation directly impacted carbon fixation, while urbanization accelerated carbon emissions and runoff rates.

For sustainable development, balancing economic growth and ecological protection requires strengthened trade-off analysis to inform regional development decisions. At the application level, ecosystem service scenario simulation and trade-off analysis effectively address land management challenges, providing scientific support for territorial planning, biodiversity conservation, and ecological compensation [25-26]. While afforestation enhances biodiversity and climate regulation, it may increase evapotranspiration and reduce water yield [27-28], affecting agricultural production [29].

Our scenario analysis (development priority, conservation priority, and balanced approaches) quantitatively simulates future ecosystem service patterns. However, future land use development faces multiple constraints and uncertainties [30-31], potentially requiring dozens of scenarios to approximate reality. Strengthening uncertainty quantification and spatial mapping will improve simulation precision and reduce trade-off analysis uncertainty.

---

5. Conclusions

This study examined the Guantian section of the Weihe River basin, estimating biodiversity, carbon sequestration, and water yield from 2000-2013 at the subbasin scale. Through land use scenario prediction and optimal Pareto frontier analysis, we optimized land use patterns for maximum ecosystem services in 2050.

1. **Temporal Trends (2000-2013)**: Total water yield increased significantly, concentrated in downstream areas. Carbon sequestration was high in the Qinling and Liupan Mountains with high vegetation cover, while the urbanized Guanzhong Plain showed low sequestration. Biodiversity quality declined overall, with high quality in the Qinling Mountains but low quality in the Guanzhong Plain due to human disturbance.
2. **Trade-off/Synergy Relationships**: Carbon sequestration and biodiversity showed synergistic but slightly weakening correlations over time. Water yield vs. carbon sequestration and water yield vs. biodiversity both exhibited trade-off relationships that strengthened initially then weakened.
3. **Optimization**: The optimal Pareto frontier and corresponding land use optimization maps provide a scientific basis for land resource management and sustainable development in the Weihe River basin. Land use transformation can maximize ecosystem service value by moving service combinations toward the Pareto frontier.

References

[1] Daily G. Nature’ s Services: Societal Dependence on Natural Ecosystems. Washington, DC: Island Press, 1997.
[2] Assessment M E. Ecosystems and Human Well-Being. Washington, DC: Island Press, 2005.

[3] Lee H, Lautenbach S. A quantitative review of relationships between ecosystem services. Ecological Indicators, 2016, 66: 340-351.
[4] Hall J M, Van Holt T, Daniels A E, Balthazar V, Lambin E F. Trade-offs between tree cover, carbon storage and floristic biodiversity in reforesting landscapes. Landscape Ecology, 2012, 27(8): 1135-1147.
[5] Thomas C D, Anderson B J, Moilanen A, Eigenbrod F, Heinemeyer A, Quaife T, Roy D B, Gillings S, Armsworth P R, Gaston K J. Reconciling biodiversity and carbon conservation. Ecology Letters, 2013, 16(S1): 39-47.
[6] Hatanaka N, Wright W, Loyn R H, Nally R M. 'Ecologically complex carbon' -linking biodiversity values, carbon storage and habitat structure in some austral temperate forests. Global Ecology and Biogeography, 2011, 20(2): 260-271.
[7] Bradshaw C J A, Bowman D M J S, Bond N R, Murphy B P, Moore A D, Fordham D A, Thackway R, Lawes M J, McCallum H, Gregory S D, Dalal R C, Boer M M, Lynch A J J, Bradstock R A, Brook B W, Henry B K, Hunt L P, Fisher D O, Hunter D, Johnson C N, Keith D A, Lefroy E C, Penman T D, Meyer W S, Thomson J R, Thornton C M, Van Der Wal J, Williams R J, Keniger L, Specht A. Brave new green world-Consequences of a carbon economy for the conservation of Australian biodiversity. Biological Conservation, 2013, 161: 71-90.
[8] Rodriguez N, Armenteras D, Retana J. National ecosystems services priorities for planning carbon and water resource management in Colombia. Land Use Policy, 2015, 42: 609-618.
[9] Onaindia M, De Manuel B F, Madariaga I, Rodriguez-Loinaz G. Co-benefits and trade-offs between biodiversity, carbon storage and water flow regulation. Forest Ecology and Management, 2013, 289: 1-9.
[10] Li Jing et al. Trade-offs and synergies among ecosystem services in the Guantian Economic Zone. Acta Ecologica Sinica, 2016, 36(10): 3053-3062.
[11] Ouyang Z Y. China' s ecological environment status and ecological civilization construction. Earth Science Advances, 2009, 24(6): 571-576.
[12] Bai Y, Ouyang Z Y, Zheng H, Li X M, Zhuang C W, Jiang B. Modeling soil conservation, water conservation and their trade-offs: a case study in Beijing. Journal of Environmental Sciences, 2012, 24(3): 419-426.
[13] Baral H, Keenan R J, Sharma S K, Stork N E, Kasel S. Economic evaluation of ecosystem goods and services under different landscape management scenarios. Land Use Policy, 2014, 39: 54-64.
[14] Kubiszewski I, Costanza R, Anderson S, Sutton P. The future value of ecosystem services: global scenarios and national implications. Ecosystem Services, 2017, 26: 289-301.
[15] Determination of organic carbon content in geochemical soil samples by potassium dichromate oxidation external heating method. Rock and Mineral Analysis, 2016, 42(4): 110-112.
[16] Zhuang C W, Jiang B. Evaluation of carbon sequestration and oxygen release value of land ecosystems in Guantian Economic Zone. Acta Ecologica Sinica, 2013, 33(9): 2907-2918.
[17] Zhou T, Shi P J, Zhu A X. Estimation of soil organic carbon storage based on remote sensing and carbon cycle process models. Journal of Remote Sensing,

2007, 11(1): 127-136.
[18] Ficklin D L, Barnhart B L. SWAT hydrologic model parameter uncertainty and its implications for hydroclimatic projections in snowmelt-dependent watersheds. Journal of Hydrology, 2014, 519: 2081-2090.
[19] Yang X, Zheng X Q, Chen R. A land use change model: integrating landscape pattern indexes and Markov-CA. Ecological Modelling, 2014, 283: 1-7.
[20] Cord A F, Bartkowski B, Beckmann M, Dittrich A, Hermans-Neumann K, Kaim A, Lienhoop N, Locher-Krause K E, Priess J, Schröter-Schlaack C, Schwarz N, Seppelt R, Strauch M, Václavík T, Volk M. Towards systematic analyses of ecosystem service trade-offs and synergies: main concepts, methods and the road ahead. Ecosystem Services, 2017.
[21] Raudsepp-Hearne C, Peterson G D, Bennett E M. Ecosystem service bundles for analyzing trade-offs in diverse landscapes. Proceedings of the National Academy of Sciences of the United States of America, 2010, 107(11): 5242-5247.
[22] Nelson E, Mendoza G, Regetz J, Polasky S, Tallis H, Cameron D, Chan K M, Daily G C, Goldstein J, Kareiva P M, Lonsdorf E, Naidoo R, Ricketts T H, Shaw M. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and trade-offs at landscape scales. Frontiers in Ecology and the Environment, 2009, 7(1): 4-11.
[23] Elmhagen B, Eriksson O, Lindborg R. Implications of climate and land-use change for landscape processes, biodiversity, ecosystem services, and governance. AMBIO, 2015, 44(S1): 1-5.
[24] Pan Y, Xu Z R, Wu J X. Spatial differences of the supply of multiple ecosystem services and the environmental and land use factors affecting them. Ecosystem Services, 2013, 5: 4-10.
[25] Bai Y. Ecosystem service trade-offs and synergies in Guantian Economic Zone. Shaanxi Normal University, 2016.
[26] Dymond J R, Ausseil A G E, Ekanayake J C, Kirschbaum M U F. Trade-offs between soil, water, and carbon-a national scale analysis from New Zealand. Journal of Environmental Management, 2012, 95(1): 124-131.
[27] Guillen E E, Murray-Rust D, Robinson D T, Barnes A, Rounsevell M D A. Modelling farmer decision-making to anticipate trade-offs between provisioning ecosystem services and biodiversity. Agricultural Systems, 2015, 137: 12-23.
[28] Landuyt D, Broekx S, Engelen G, Uljee I, Van der Meulen M, Goethals P L G. The importance of uncertainties in scenario analyses-A study on future ecosystem service delivery in Flanders. Science of the Total Environment, 2016, 553: 504-518.
[29] Gret-Regamey A, Brunner S H, Altwegg J, Bebi P. Facing uncertainty in ecosystem services-based resource management. Journal of Environmental Management, 2013, 127(S1): S145-S154.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.