

Multi-objective Linear Programming-Based Trade-off Optimization of Ecosystem Services in the Jiajiyu Small Watershed: A Postprint

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Abstract

The Loess Plateau is one of the regions with the most severe soil erosion in China, where regional ecosystem services have degraded. Small watersheds constitute the primary sites where soil erosion occurs, and how to trade off various ecosystem services while enhancing soil conservation services represents an important component of current ecosystem service management. This study selected Jiajiyu, a typical small watershed in the Loess Plateau, with 2012 as the baseline year and 2022 as the planning target year. Based on statistical yearbooks and survey data, the market value method, shadow price method, shadow project method, replacement cost method, and opportunity cost method were employed to estimate the ecosystem service values of different land use types. Using multi-objective linear programming, ecosystem services were categorized into provisioning services, soil conservation services, and other services. The values of these three categories served as sub-objectives for trade-off analysis, while the total ecosystem service value functioned as the overall objective for constructing the objective function. Based on land area, grain and oil security, and the slope suitability of various land use types, 35 variables were utilized to formulate 17 constraint equations. Trade-off optimization of ecosystem services in the small watershed was achieved by adjusting land use types in Jiajiyu. The results indicate that the ecosystem service value of Jiajiyu was primarily constrained by sloping farmland and barren grassland, which occupied large proportions but exhibited low ecosystem service values. Following trade-off optimization, sloping farmland and barren grassland were mainly converted into arbor forest and terraced fields with higher ecosystem service values, resulting in significant improvement of the land use structure. The total ecosystem service value increased by 9.23%, while provisioning services, soil conservation services, and other services increased by 6.24%, 9.81%, and 17.35%, respectively. The incremental values of the three categories accounted for 25.96%, 54.42%, and 19.62%

of the total ecosystem service value increment, respectively. Compared with optimization results using only provisioning services, soil conservation services, other services, or total service value as the objective function, the optimization with three sub-objectives yielded more coordinated outcomes, with all three benefits showing significant increases. In terms of spatial distribution, the growth rates of ecosystem service values varied significantly across different ecological function zones, with the highest growth rate for other services in the upstream region, the highest for soil conservation services in the midstream region, and the highest for provisioning services and total services in the downstream region, consistent with the ecological function zoning of the upper, middle, and lower reaches of Jiajiyu. The study fully considered land use suitability, emphasized soil conservation services while ensuring provisioning services, and optimized other services, thereby improving all comprehensive management benefit evaluation indicators, which aligns with the actual conditions of small watersheds in the Loess Plateau.

Full Text

Preamble

Multi-objective Linear Programming-Based Trade-off and Optimization of Ecosystem Services in Jiajiyu Small Watershed in the Loess Plateau, China

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Abstract

The Loess Plateau is one of China's most severely soil-eroded regions, with significant regional ecosystem service degradation. Small watersheds constitute the primary locations where soil erosion occurs, making the evaluation of trade-offs among various ecosystem services a critical component of current ecosystem service management, particularly when enhancing water and soil conservation services. This study selected Jiajiyu, a typical small watershed on the Loess Plateau, using 2012 as the baseline year and 2022 as the planning target year. Based on statistical yearbook and survey data, we estimated ecosystem service values for different land-use types using market value, shadow price, shadow

engineering, alternative cost, and opportunity cost methods. Employing multi-objective linear programming, we categorized ecosystem services into supply services, water and soil conservation services, and other services, using their values as trade-off sub-objectives and total ecosystem service value as the overall objective function. We developed 17 constraint equations based on 35 decision variables, incorporating land area controls, grain and oil security, and slope suitability constraints for different land-use types. By adjusting land-use types in Jiajiyu, we achieved trade-off optimization of small watershed ecosystem services.

The results showed that Jiajiyu's ecosystem service values were primarily constrained by slope farmland and waste grassland—land-use types with large areal proportions but relatively low ecosystem service values. Through optimization, slope farmland and waste grassland were mainly converted to arbor forest and terraces, which have substantially higher ecosystem service values. The land-use structure improved significantly, with total ecosystem service value increasing by 9.23%. Supply service, water and soil conservation service, and other service values increased by 6.24%, 9.81%, and 17.35%, respectively, accounting for 25.96%, 54.42%, and 19.62% of the total ecosystem service value increase. Compared with optimization results using only supply service, water and soil conservation service, other services, or total service value as single objective functions, the three-sub-objective optimization produced more coordinated results with significantly increased benefits across all three categories. Spatially, growth rates of ecosystem service values varied markedly among different ecological functional zones, with the highest growth rates observed for other services in the upper reaches, water and soil conservation services in the middle reaches, and supply and total services in the lower reaches—consistent with the ecological functional zoning of Jiajiyu's upper, middle, and lower reaches. This approach fully considered land-use suitability, optimized other services while ensuring supply services, highlighted water and soil conservation services, and improved comprehensive management evaluation indices, aligning with actual conditions in Loess Plateau small watersheds.

Keywords: ecosystem service trade-off; small watershed; Loess Plateau; multi-objective linear programming; land use

1. Introduction

Rapid socioeconomic and population growth, coupled with excessive demands on ecosystem services, has led to the degradation of 60% of global ecosystem functions [1], affecting human survival, development, and regional ecological security. A primary cause is the lack of effective ecosystem service management [2]. Due to the diversity of ecosystem types and the complexity of their interrelationships, overemphasizing particular ecosystem services may lead to declines in others [3-4]. Balancing and coordinating various ecosystem services repre-

sents an effective means to promote ecosystem function restoration and reduce human disturbance on natural environments [5-7].

Among methods for ecosystem service trade-off analysis, threshold analysis can examine trade-off relationships between different ecosystem types [8], but suffers from inherent uncertainties. Extreme value analysis assumes linear relationships between conflicting objectives, which is overly simplistic and static. The conversion of natural capital to economic capital through coefficient adjustment has limited application, primarily in water resource management [10]. Model analysis can predict potential changes in ecosystem services under different scenarios to reduce conflicts with biodiversity [11]. Multi-objective analysis [12] can address complex conflicts and is suitable for systematic analysis of land-use transformation and adjustment [13-14]. The InVEST model is applicable for large-scale studies [6]. All these methods essentially involve land-use adjustments.

Watersheds are regions with strong interactions between society, economy, and nature, where ecosystem degradation is prominent [15]. Achieving sustainable socioeconomic development through virtuous material cycles and sustainable natural resource utilization represents the goal of watershed ecosystem management [16]. China's small watershed soil and water conservation comprehensive management models have primarily relied on experimental observations and pilot projects [17-19], accumulating substantial practical experience and forming a series of demonstration achievements and management models [20-21]. However, these approaches have limitations including long implementation periods, high investment, and poor replicability [22]. Process simulation and scenario analysis can trade off and predict future watershed states, providing important references for policy-making under uncertainty [25]. Calculating economic, ecological, and social benefits under various management measures [23-24], optimizing small watershed management plans from an ecosystem service perspective has become a research hotspot [26], focusing on analyzing human activity impacts on watershed ecosystem services and balancing ecological and economic relationships [8,27-29].

The Loess Plateau's hilly and gully region has severe soil erosion [30], which significantly constrains agricultural economic development. Long-term irrational land use further exacerbates soil erosion and declining land productivity [31]. Jiajiyu small watershed implemented the World Bank's second phase soil and water conservation loan project in 2003 and the UK grant small watershed management project during 2007-2011 [32], effectively controlling soil erosion. However, trade-offs among various ecosystem services have gradually emerged in subsequent management efforts. This study uses Jiajiyu as the research area, employing multi-objective linear programming based on ecosystem service value assessment to set supply services, water and soil conservation services, and other services as trade-off objectives. By designing planning variables and constraint equations according to land-use optimization directions and existing management measures, we achieve trade-off optimization of ecosystem services

to provide references for comprehensive small watershed management.

2. Study Area

Jiajiyu small watershed is located in the southeastern part of Kongtong District, Pingliang City, Gansu Province (106°57'02" E – 107°01'59" E, 35°14'18" – 35°18'00" N), covering an area of 28.2 km². It is a first-order tributary of the Jing River and belongs to the Loess Plateau residual hilly and gully region. The watershed has an elevation range of 1382–1785 m, with a hilly and gully landscape dissected into tablelands and terraces. The surface is covered by loess with well-developed “V”-shaped gullies and a gully density of 1.34 km/km². The region has a temperate semi-arid climate with mean annual precipitation of 511 mm and mean annual temperature of 8.6°C. The average annual soil erosion modulus is 6600 t/km².

Agriculture dominates land use, with wheat and corn as main crops and small amounts of alfalfa. The downstream area has apple and pear orchards. Main livestock include cattle, sheep, and chickens. The population is 7,806 (2012), predominantly Hui ethnicity. Natural slopes below 5° cover 454 hm² (16.1%); 5°–15° slopes cover 1194 hm² (42.3%); 15°–25° slopes cover 713 hm² (25.3%); 25°–35° slopes cover 296 hm² (10.5%); and slopes >35° cover 163 hm² (5.8%).

[Figure 1: see original paper] Location and slope distribution of Jiajiyu small watershed

3. Data Sources

Remote sensing data consisted of GeoEye imagery with 0.5 m resolution. DEM and 1:50,000 topographic maps were obtained from the National Fundamental Geographic Information System. The remote sensing imagery underwent radiometric and geometric correction. Given the watershed's elongated shape, we used supervised classification combined with field verification to interpret land-use type distributions. Grain yield data were obtained from the *Pingliang Kongtong District Statistical Yearbook (2012)*, literature, and 2012 household questionnaires in Jiajiyu.

4. Ecosystem Service Valuation Methods

Ecosystem services in the small watershed were categorized into supply services, regulation services, support services, and cultural services. Supply service values were assessed using market value methods. Regulation and support services used shadow price, shadow engineering, alternative cost, and opportunity cost

methods. Due to limited research data on water bodies and unused land in Jiajiyu, we applied Xie Gaudi' s equivalent table [33] for assessment. Cultural services (leisure, tourism, scientific research, and education) were not evaluated due to the absence of tourist attractions and reliable calculation data.

Ecosystem service types, evaluation indices, and methods

4.1 Product Supply

Product supply service values were evaluated using market value methods with 2012 local purchase prices. Due to soil and water conservation requirements, Jiajiyu' s waste grassland and closed forest areas prohibit logging and grazing. Main products include corn, wheat, crop straw, and standing timber. We did not calculate product supply values for waste grassland and closed forest areas.

4.2 Carbon Sequestration and Oxygen Release

Based on the photosynthesis equation, we calculated carbon sequestration and oxygen release according to net primary productivity (NPP) of vegetation types [34]. Afforestation cost methods were used for valuation [35]. NPP for arbor forest and economic forest were 352.93 t/hm² and 260.9 t/hm², respectively [37]. Orchards and closed forest were converted using green equivalent coefficients of 0.47 and 0.73. Waste grassland NPP was 1.445 t/hm² [39], and artificial grassland NPP was 12.50 t/hm² based on survey results. Since cropland is annual and straw/artificial grass are used for livestock feed, we did not calculate farmland carbon sequestration values for the trade-off optimization timeframe. Artificial grassland was evaluated based on below-ground biomass.

4.3 Water Conservation

We calculated water retention using shadow engineering methods based on water conservation rates of different soil and water conservation measures. Due to lack of bare land runoff depth monitoring data, we conservatively estimated using the average annual runoff depth of 50 mm from the *Pingliang Kongtong District Jiajiyu Demonstration Watershed Planning Report*. Local empirical values were used for water conservation rates, with water storage costs at 2.5 yuan/m³.

4.4 Environmental Purification

Environmental purification services focused on dust retention, evaluated using alternative cost methods. Dust retention capacities were: slope farmland and terraces 0.12 t/hm², economic forest and closed forest (converted to arbor forest) 0.95 t/hm², waste grassland and artificial grassland 10.11 t/hm², and arbor forest 20.61 t/hm² [41-43]. Dust removal cost was 170 yuan/t [44].

4.5 Soil Conservation

Soil conservation value comprises three components: reduced sedimentation, reduced land abandonment, and soil fertility maintenance. We used the Revised Universal Soil Loss Equation (RUSLE) [45] to estimate potential and actual soil erosion, with the difference representing soil conservation. The rainfall erosivity factor (R) was $51.58 \text{ MJ} \cdot \text{mm}/(\text{hm}^2 \cdot \text{h} \cdot \text{a})$, soil erodibility factor (K) was $0.470 \text{ t} \cdot \text{h}/(\text{MJ} \cdot \text{mm})$, and LS factor was obtained from DEM hydrological analysis. Vegetation cover (C) and conservation practice (P) factors were derived from literature [46-47].

4.6 Nutrient Cycling

Nutrient cycling value was calculated based on annual NPP and nutrient allocation rates in ecosystems. Farmland NPP was derived from economic yield, economic coefficient, and water content [49-52]. Artificial grassland, with longer planting duration, maintains nutrient cycling through above-ground growth and return; we calculated nitrogen, phosphorus, and potassium content in above-ground annual NPP.

5. Multi-Objective Linear Programming Model

5.1 Parameter Selection

Severe soil erosion in Jiayiyu occurs mainly in the upper and middle reaches, related to slope and land-use distribution. Slope farmland and waste grassland on $<15^\circ$ and 15° - 25° slopes account for 23.09% and 58.16% of the upper reach area, respectively. In the middle reaches, slope farmland and waste grassland occupy 32.93% and 20.49% of the area, while terraces and arbor forest dominate (46.58%). The lower reaches are dominated by economic forest and construction land (56.44% and 39.39%). Based on Jiayiyu's ecological functional zoning (upper: water source conservation; middle: agricultural development; lower: ecological economy) and slope suitability [53], we identified optimization directions for different slopes and land-use types.

5.2 Decision Variables

We designed 35 decision variables representing adjustable areas of different land-use types across slope gradients and ecological zones (Table 3). Variables included conversions from slope farmland to terraces, arbor forest, economic forest, orchards, artificial grassland, and closed forest; and conversions from waste grassland to artificial grassland, economic forest, arbor forest, and closed forest.

Slope suitability constraints for land-use optimization in Jiayiyu

Design of decision variables

5.3 Objective Functions

Overemphasizing particular ecosystem services may cause declines in others (e.g., supply vs. other services) [55]. Considering Jiajiyu' s severe soil erosion, we established three sub-objectives: supply service value (F_1), water and soil conservation service value (F_2), and other service value (F_3), with total ecosystem service value as the overall objective. To convert multi-objectives into a single target, we normalized different ecosystem service values and performed linear weighted summation using weights w_1, w_2, w_3 (each = 1/3).

5.4 Constraints

Grain and oil production constraints: Based on 2012 surveys, terrace wheat yield was 2632 kg/hm², corn yield 7806.08 kg/hm², and rapeseed yield 1683.82 kg/hm². Per capita wheat consumption was 391.90 kg/a, corn 125.16 kg/a, and oil 30 kg/a. With a natural population growth rate of 6‰, the planning period population should be controlled at 8,353. We established constraints for wheat, corn, and oil production demands.

Land area constraints: Based on 2012 data, optimized land-use type areas must not exceed adjustable areas under slope suitability constraints. We established 17 constraint equations incorporating population, grain/oil demand, and land area limitations.

Design of constraint equations

5.5 Sensitivity Analysis

To verify ecosystem service value coefficient accuracy, we calculated sensitivity indices (CS) by adjusting coefficients $\pm 50\%$ [56]. $CS < 1$ indicates inelasticity (low dependency), while $CS > 1$ indicates high sensitivity.

5.6 Comprehensive Management Benefit Evaluation

Water and soil conservation benefits: Calculated based on reduced water and soil loss. Water conservation benefits used engineering costs; sediment reduction benefits used sediment reduction costs.

Economic benefits: Derived from land conversion measures (terrace construction, economic forest, orchard planting). Fruit prices were based on survey data.

Ecological benefits: Evaluated through forest coverage rate and comprehensive carbon sequestration capacity per unit watershed area [57].

6. Results

6.1 Ecosystem Service Value Assessment

In 2012, orchards had the highest per-unit supply service value (26,325.74 yuan/hm²), followed by economic forest. Arbor forest had the highest per-unit water and soil conservation value (12,127.60 yuan/hm²), followed by closed forest. Water bodies had the highest per-unit other service value. Overall ranking: orchard > economic forest > arbor forest > closed forest > terrace > artificial grassland > waste grassland > slope farmland > river > bare land.

Jiajiyu' s low per-unit ecosystem service value primarily resulted from large proportions of slope farmland (7.53% of total area, contributing only 3.64% to water conservation value) and waste grassland (7.96% of area, with no product supply value due to grazing prohibition). These required optimization through land-use adjustment.

Per-unit ecosystem service values of land-use types in Jiajiyu (2012)

6.2 Optimal Solution and Land-Use Change

Using Excel' s solver function with target cells and constraint cells, we obtained optimal decision variable values (Tables 6-7) and land-use transition matrices (Table 8).

Water and soil conservation service values of decision variables in 2022

Optimal values of decision variables

Land-use transition matrix of Jiajiyu before and after optimization

After optimization, all slope farmland and waste grassland were converted to other land-use types. Terraces became the dominant land-use type (885.70 hm², 31.40% of watershed), followed by closed forest (489.71 hm², 34.92%). Slope farmland was preferentially converted to arbor forest (46.78% of converted area) and terraces (40.45%). Waste grassland was converted to economic forest (35.35%), arbor forest (33.65%), and closed forest (31.00%).

6.3 Spatial Land-Use Changes

Pre-optimization, terraces and slope farmland dominated (885.70 hm² and 212.45 hm², respectively). Post-optimization, slope farmland was preferentially converted to arbor forest and closed forest in upper reaches, and to economic forest and orchards in lower reaches. Waste grassland in upper reaches was entirely closed for forest regeneration, while middle reaches converted mainly to arbor forest and economic forest, and lower reaches to economic forest. This spatial pattern aligns with ecological functional zoning, slope gradients, and soil fertility conditions.

[Figure 2: see original paper] Soil erosion degree distribution of Jiajiyu small watershed

[Figure 3: see original paper] Spatial distribution of land-use types before and after optimization

6.4 Ecosystem Service Value Changes

Post-optimization, supply service, water and soil conservation service, and other service values increased by 6.24%, 9.81%, and 17.35%, respectively, with total ecosystem service value increasing by 9.23%. The three sub-objectives accounted for 25.96%, 54.42%, and 19.62% of the total value increase. Supply service proportion decreased slightly while other services increased significantly, optimizing the service structure.

Comparison of ecosystem service values before and after optimization

Spatial analysis revealed distinct changes across reaches: upstream supply service decreased 4.61% (due to conversion to high-conservation-value forests), while middle and downstream increased 9.87% and 16.24%. Water and soil conservation service increased most in middle reaches (71.21% of total increase) due to large-scale conversion to arbor forest and terraces. Other services increased most in upper reaches (43.54% of total increase) through closed forest and arbor forest establishment.

[Figure 4: see original paper] Spatial distribution of ecosystem service value changes before and after optimization

6.5 Sensitivity Analysis

Pre- and post-optimization sensitivity indices for all land-use types were <1 , indicating inelasticity. Terraces showed highest sensitivity (0.41). Post-optimization, sensitivity ranking changed to terraces $>$ economic forest $>$ arbor forest, reflecting their increased areal proportions. The low sensitivity values confirm result reliability.

Ecosystem service value change rates and sensitivity coefficients from 50% coefficient adjustment

6.6 Comprehensive Management Benefits

Optimization increased annual water retention by $11.02 \times 10^3 \text{ m}^3$ (44.22% increase) and reduced sediment by 4,406.67 t. Terrace yields increased from 3,865.95 to 5,219.04 kg/hm². Forest coverage increased from 20.19% to 32.66%, and comprehensive carbon sequestration capacity rose from 1.14 to 1.37 t/hm². Economic benefits increased 1.59×10^4 yuan. All ecological, economic, and social benefits improved significantly.

7. Discussion and Conclusion

This study integrated slope suitability, ecological functional zoning, and typical Loess Plateau watershed management measures to conduct ecosystem service trade-off optimization in Jiajiyu using multi-objective linear programming. The low ecosystem service values of slope farmland and waste grassland, combined with their large areal proportions, were identified as primary constraints. Optimization converted these mainly to arbor forest, economic forest, and closed forest, significantly increasing all three service values while meeting slope suitability and food security constraints.

Spatial differentiation in optimization results aligned with functional zoning: upper reaches prioritized water conservation (other services), middle reaches emphasized agriculture (water/soil conservation), and lower reaches focused on economic development (supply services). This approach balanced multiple objectives more effectively than single-objective optimizations, which either maximized supply services at the expense of conservation or vice versa.

The study focused on long-term benefits, excluding farmland carbon sequestration and considering only dust retention for environmental purification. This avoided overestimation of other services while highlighting water and soil conservation—a key issue in the Loess Plateau. The results demonstrate that land-use adjustment is crucial for improving ecosystem services, particularly converting erosion-prone slope farmland and waste grassland to suitable vegetation types. Future research should integrate engineering measures (gully head protection, small dams), policy instruments (closing policies, compensation mechanisms), and community-based management to further enhance watershed sustainability.

The optimization framework provides a scientific basis for Jiajiyu's future management, offering reference for similar small watersheds in the Loess Plateau region.

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