Supplementary Material for

Township-Level Ecological Management for Enhanced Ecosystem Services in the Qinling Mountains

The following methodology complements the materials and methods section of the main text:

Carbon storage estimation The Carbon module of the InVEST model was used to estimate the carbon storage in the study area based on the carbon density values of each category with the following formula (Sharp et al., 2018):

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (S1)$$

Where C_{total} is the total carbon stock in the ecosystem; C_{above} is the aboveground carbon stock in the ecosystem; C_{below} is the belowground carbon stock in the ecosystem; C_{soil} is the soil carbon stock in the ecosystem; and C_{dead} is the dead organic matter in the ecosystem.

Water conservation capacity estimation The Water Yield module of InVEST model was utilized to calculate the water yield through the following formula (Budyko, 1974; Yu et al., 2021):

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) P_x \quad (S2)$$

$$\frac{AET_{xj}}{P_x} = \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + \frac{1}{R_{xj}}} \quad (S3)$$

$$\omega_x = Z \frac{AWC_x}{P_x} \quad (S4)$$

$$R_{xj} = \frac{k_{xj} ET_{0x}}{P_x} \quad (S5)$$

Where Y_{xj} is the water yield for grid unit x on the specific land use/land cover (LULC) type j. AET_{xj} indicates the annual actual evapotranspiration for grid unit x on LULC j, and P_x is annual precipitation for the same grid unit. The parameter ω_x is a non-physical parameter of grid x, which characterizes the natural climate-soil properties. R_{xj} signifies the Budyko Aridity index for grid x on LULC j. Z is a seasonal constant named Zhang

parameter with values varying from 1 to 30, and AWC_x refers to the available soil moisture of grid x. Additionally, k_{xj} is the plant evapotranspiration coefficient of grid x associated with LULC j, and ET_{0x} represents the potential evapotranspiration of grid x.

Soil retention estimation The Sediment Delivery Ratio module of InVEST model was used to simulate the soil retention function with Qinling Mountain region, in which the soil retention was calculated as the discrepancy between the potential and actual soil loss using the following formula (Huang and Wu, 2023):

$$SC_x = R_x \times K_x \times LS_x \times (1 - C_x P_x) \quad \text{(S6)}$$

Where SC_x is the quantity of soil retention for grid unit x. R_x is the rainfall erosion index, K_x is the soil erosion factor and LS_x stands for the slope length-gradient factor for grid x, respectively. C_x denotes the crop/vegetation and management factor, while P_x is the support practice factor for grid x.

Water purification capacity estimation The water purification function was simulated based on the Nutrient Delivery Ration module of the InVEST model, which employed grids as fundamental units to compute the delivery and retention of nutrients N and P with each unit, and ultimately simulated the overall nitrogen and phosphorus output from the ecosystem. A higher output indicates a less water purification effect. The calculation formulas are as following (Zhang et al., 2022):

$$\mathrm{NDR_i}=\mathrm{NDR_{0,i}}\left[1+\exp\left(\frac{\mathrm{IC_i}-\mathrm{IC_0}}{\mathrm{k}}\right)\right]^{-1} \quad \text{(S7)}$$

where $NDR_{0,i}$ was the proportion of nutrient that was not retained by downstream pixels, IC_i was a topographic index, and IC_0 and k were calibration parameters. $NDR_{0,i}$ was based on the maximum retention efficiency of the land between a pixel and the stream:

$$\mathrm{NDR_{0,i}}=1-\mathrm{eff_i^{'}} \quad \text{(S8)}$$

where, $eff_i^{'}$ was the total retention, which was capped by the maximum retention value that LULC types along the flow path contribute.

References

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Table S1. Correlation coefficient between InVEST model and IUEMS model for soil retention results

	Year	R
Correlation Coefficient (InVEST & IUEMS)	1980	0.6223
	1990	0.6020
	2000	0.6205
	2010	0.6131
	2020	0.6041
	AVE.	**0.6124**

Table S2. Application and accuracy verification at different research scales

	Year	Township	County	City
Area Variability	1980-1990	10.9%	5.5%	41.7%
	1990-2000	10.6%	6.3%	22.3%
	2000-2010	3.4%	0.0%	19.4%
	2010-2020	7.9%	2.7%	21.7%
	1980-2020	**14.2%**	**12.7%**	**19.4%**
Administrative unit Variability	1980-1990	11.5%	2.6%	33.3%
	1990-2000	11.8%	7.7%	16.7%
	2000-2010	4.6%	0.0%	16.7%
	2010-2020	11.3%	5.1%	33.3%
	1980-2020	**17.7%**	**7.7%**	**16.7%**
Correlation Coefficient (Pixel-based ESB & Scale-based ESB)	1980	50.6%	30.7%	22.7%
	1990	50.7%	27.9%	17.2%
	2000	53.4%	43.7%	35.1%
	2010	52.3%	24.2%	18.0%
	2020	53.6%	45.5%	35.3%
	AVE.	**52.1%**	**34.4%**	**25.7%**

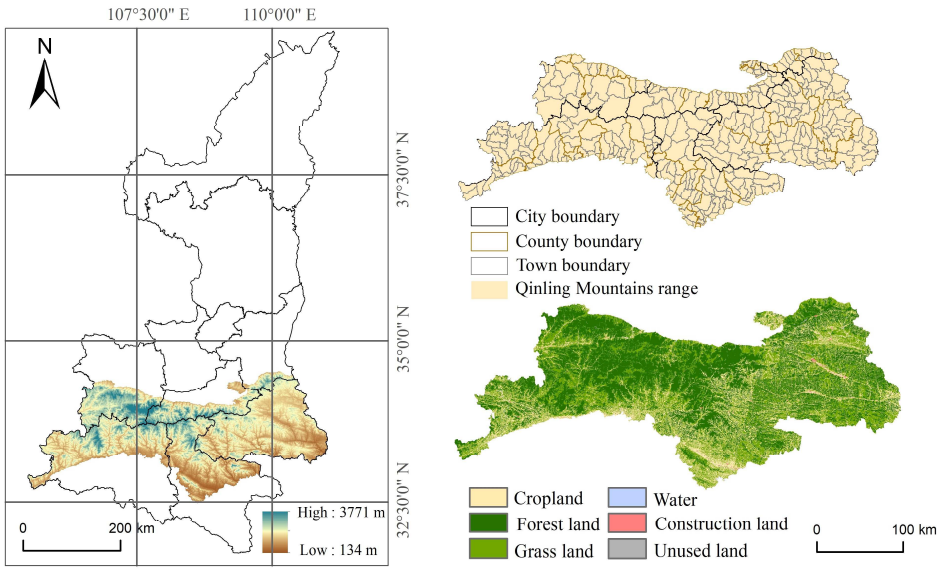


Figure S1. Location of Qinling Mountains, administrative boundaries and the land use types in 2020.

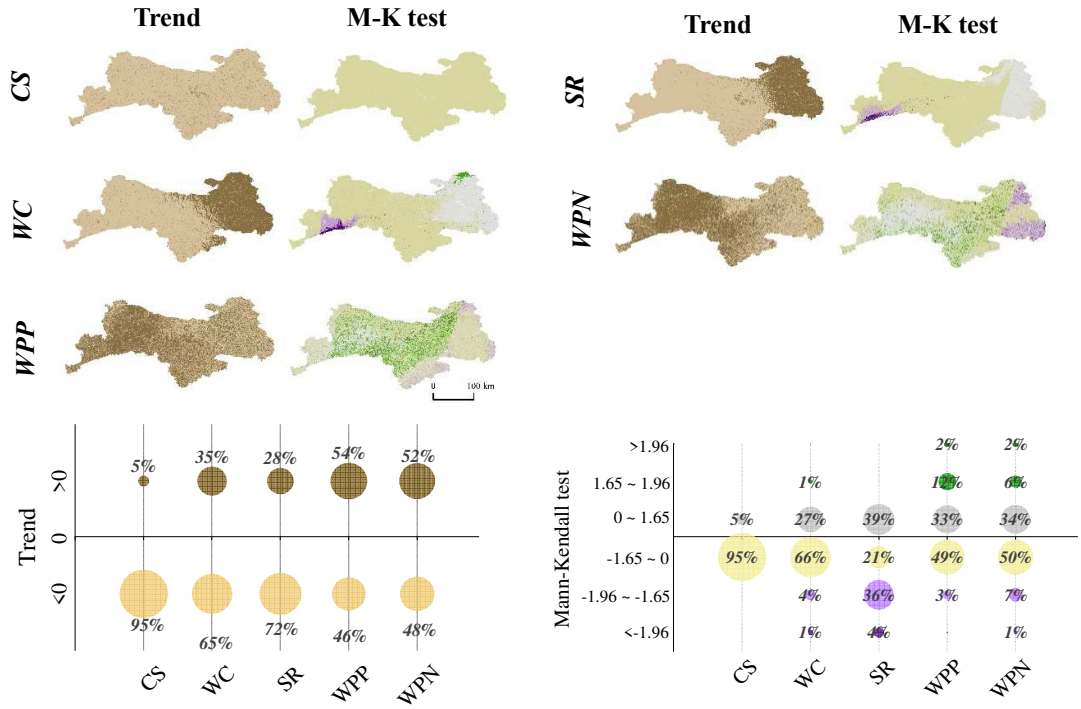


Figure S2. Dynamic trends and Mann-Kendall (M-K) test results of ecosystem services and in Qinling Mountains from 1980 to 2020. CS: carbon sequestration (Mg C/ha); WC: water conservation (mm); SR: soil retention (Mg/ha); WPP: water purification for phosphorus; WPN: water purification for nitrogen. The results in M-K test: >1.96 and <-1.96 are significant differences with $P < 0.05$; the statistical significance of 1.65~1.96 and -1.96~-1.65 is at $P < 0.1$ level.

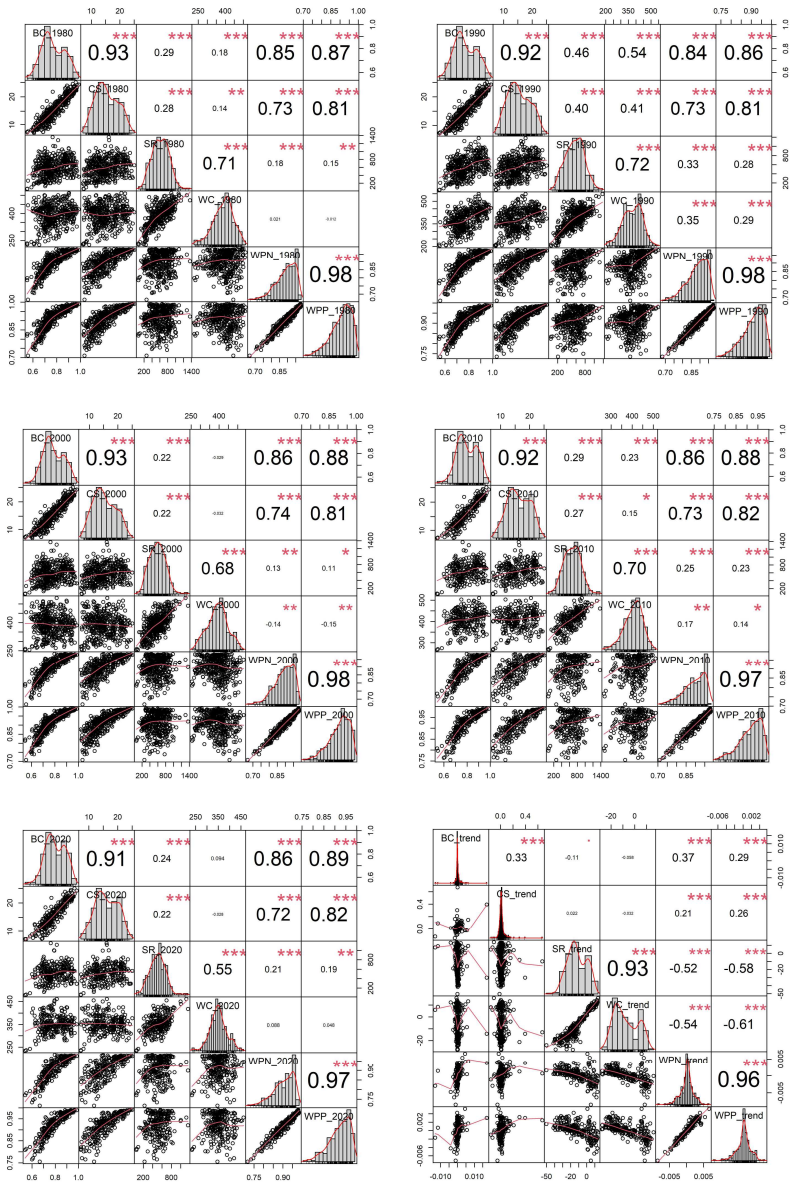


Figure S3. Spearman correlations between ESs in Qinling Mountains in 1980, 1990, 2000, 2010 and 2020, and spearman correlations between ES tends. Asterisks indicate the degree of significance (*** for $P < 0.001$ highly significance, ** for $P < 0.01$ significance, *for $P < 0.05$ statistic difference). BC: biodiversity conservation.

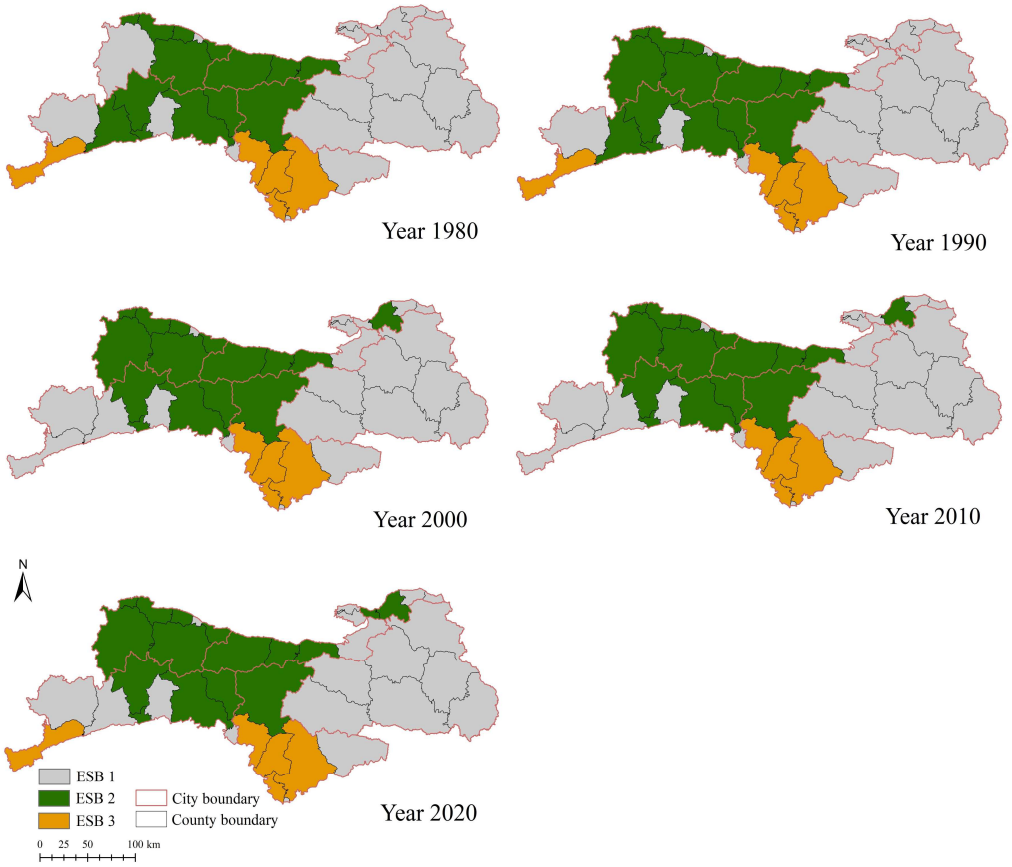


Figure S4. The spatial distribution of ecosystem service bundles in Qinling Mountains from 1980 to 2020 at the county scale.

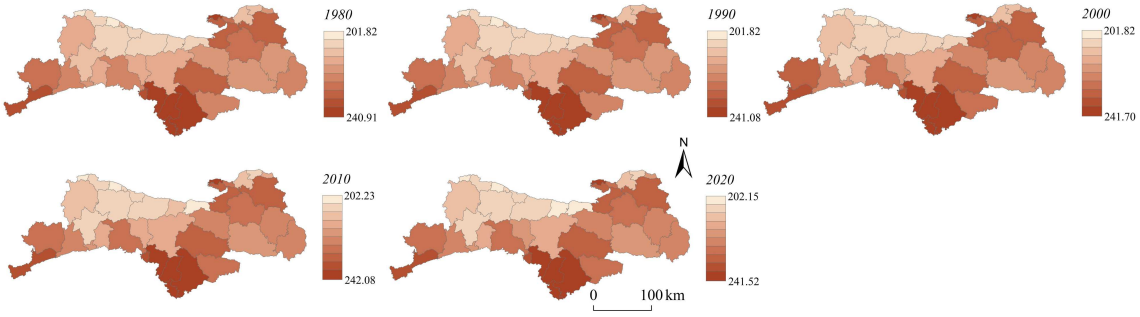


Figure S5. Land-use degree comprehensive index (La) for the Qinling Mountains at the county scale in 1980, 1990, 2000, 2010, and 2020.

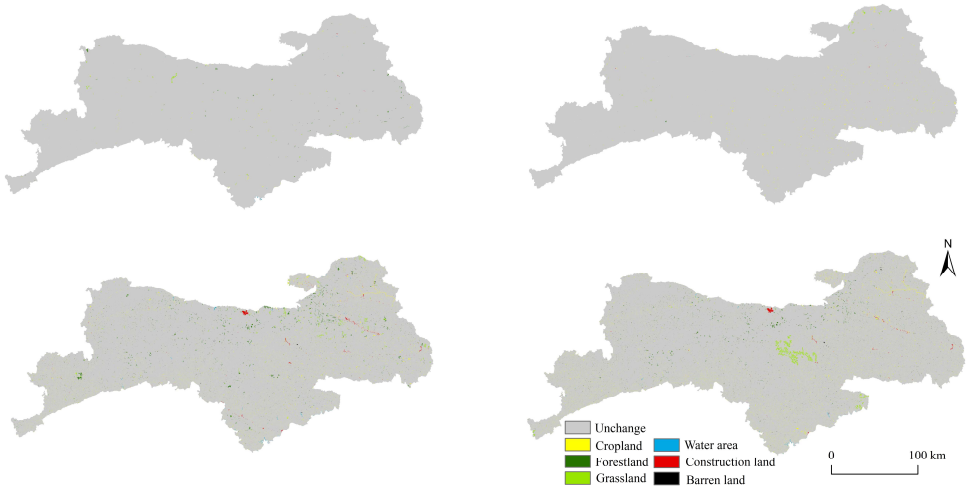


Figure S6. The evolution of the Qinling ecosystems over five periods from 1980 to 2020 (top left: changes from 1980-1990, top right: changes from 1990 to 2000, bottom left: changes from 2000-2010, bottom right: changes from 2010-2020).