Article

Prediction and Evolution of Carbon Storage of Terrestrial Ecosystems in the Qinling Mountains North Slope Region, China

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Abstract: The Qinling Mountains north slope region constitutes a vital terrestrial ecosystem reserve within China. This study employs land use and land cover (LULC) data spanning from 1990 to 2020. Utilizing methodologies encompassing land use classification, transfer matrix analysis, and the application of the PLUS and InVEST models, this research endeavors to elucidate the spatial-temporal dynamics of land use patterns and associated carbon storage in the region. These analyses are conducted within the context of four prospective scenarios: Natural Development Priority, Arable Land Protection Priority, Ecological Protection Priority, and Urban Development Priority, all projected onto the landscape for 2030. Notably, our findings reveal a consistent decline in carbon storage across all four scenarios for 2030 compared to the baseline year 2020. This stark reality presents substantial challenges to achieving the region's targets of carbon peaking and eventual carbon neutrality. Furthermore, this paper meticulously delineates six key drivers contributing to this decline in carbon storage. In conclusion, it proffers nine strategic recommendations aimed at augmenting carbon storage, with an overarching objective of establishing a harmonized mechanism capable of balancing urban development, safeguarding cultivated land, fortifying ecological preservation, and enhancing carbon sequestration within the area.

Keywords: carbon storage; InVEST model; PLUS model; land use; Qinling Mountains north slope region

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Supplementary Material

Land use transfer matrix model

In the land use transfer matrix (Table S1), the rows indicate the land use type at time point T1 and the columns indicate the land use type at time point T2. *Pij* indicates the area converted from land type i to land type j during T1-T2; *Pii* indicates the area where land use type i remained unchanged during T1-T2. *Pi+* indicates the area of land type i at time point T1. *P+j* denotes the area of land use type j at time point T2. (*Pi+* - *Pii*) is the area of land type i decreased during T1-T2; (*P+j* - *Pjj*) is the area of land type j increased during T1-T2.

Table S1. A sample of land use transfer matrix.

		T2				*Pi+*	Decrease
		A1	A2	…	An		
T1	A1	*P11*	*P12*	…	*P1n*	*P1+*	*(P1+ - P11)*

A2	*P21*	*P22*	…	*P2n*	*P2+*	*(P2+ - P22)*
…	…	…	…	…	…	…
An	*Pn1*	*Pn2*	…	*Pnn*	*Pn+*	*(Pn+ - Pnn)*
P+j	*P+1*	*P+2*	…	*P+n*	1	
Increase	*(P+1 - P11)*	*(P+2 - P22)*	…	*(P+n - Pnn)*		

Based on the land use transfer matrix, this paper investigates the net change data, the exchange change data and the total change data of land use.

First of all, the net change data of land use is the absolute change of land use type quantity, which is the most commonly used information in land use change analysis. However,due to the fixed and unique spatial location of land use,the net change data of land use cannot truly reflect the dynamic evolution of land use. When the net change data is zero,it does not necessarily mean that there is no change in the land use landscape, but most likely there is a change in the spatial location of land use types. In this paper, we use Dj to denote the net change data of land use. The penultimate row in Table S1 gives the number of each land use type in period T2, and the penultimate column gives the number of each land use type in period T1, and the difference between them is the net change data of each land use type. Its general formula is as follows:

$$Dj=\mathrm{MAX}(Pi+ - Pii, P+j - Pjj)-\mathrm{MIN}(Pi+ - Pii, P+j - Pjj)=|P+j - Pi+| \quad \text{(S1)}$$

Secondly, the exchange change data of land use is the method to quantitatively analyze the conversion between different land use types. This method makes up for the deficiency that the net change data cannot truly reflect the dynamic change of land use, and truly reflects the land use change spatially by quantitative methods.Its general formula is as follows:

$$Sj=2\times\mathrm{MIN}(Pi+ - Pii, P+j - Pjj) \quad \text{(S2)}$$

In the above formula, Sj denotes the exchange change data of j land use types.

Thirdly, the total change data of land use is the sum of the net change data and the exchange change data.The calculation formula of the total change data of land use is:

$$Cj=Dj+Sj=\mathrm{MAX}(Pi+ - Pii, P+j - Pjj)+\mathrm{MIN}(Pi+ - Pii, P+j - Pjj)=|P+j + Pi+| \quad \text{(S3)}$$

In formula (S3), Cj denotes the total change data of j land use types.

In particular, it is important to point out that since the whole region is a closed system, the addition and reduction are a mutual process,and the increase of one land use type within the system is necessarily accompanied by the reduction of another land use type. Therefore, for the whole region, the total addition and the total decrease of the land use of the whole region are equal, and the sum of the total change data of the whole region is equal to them. And the total net change data and the total exchange data of the whole regional land use are half of the sum of the net change data and the exchange data of each land use type, respectively.Hence,according to Table S1,we can obtain the table of the land use change information between T1 and T2 (Table S2).

Table S2. Land use change information between T1 and T2.

Type	Increase	Decrease	The total change data	the exchange change data	the net change data
		T1-T2			
A1	*(P+1 - P11)*	*(P1+ - P11)*	*C1*	*S1*	*D1*
A2	*(P+2 - P22)*	*(P2+ - P22)*	*C2*	*S2*	*D2*
…	…	…	…	…	…
An	*(P+n - Pnn)*	*(Pn+ - Pnn)*	*Cn*	*Sn*	*Dn*

Total $\sum_{n=1}^{m}$	$\sum(P_{+n}-P_{nn})$	$\sum(P_{n+}-P_{nn})$	$\sum C_n$	$0.5\times\sum S_n$	$0.5\times\sum D_n$

PLUS model

The Land Expansion Analysis Strategy (LEAS)

The LEAS module analyzes the land use data on two different dates to obtain the changing pattern of each land use type through the change of growth patches. It uses the Random Forest Classification (RFC) to characterize the land use change in a specific time interval, exploring the relationship between drivers and land use types and obtaining the development probability of each land use type. The formula of LEAS is as follows:

$$P_{i,k(X)}^{d}=\frac{\sum_{n=1}^{M} I[h_n(X)=d]}{M} \tag{S4}$$

In formula (S4), X is a vector composed of driving factors; M is the number of regression trees; d takes the value of 0 or 1, 1 means other land use types can be transformed into land use type k, 0 means other land use types cannot be transformed into land use type k; $h_n(X)$ is the type of land use prediction by the calculation at a regression tree value of n; $I[h_n(X)=d]$ is the exponential function of the regression tree; $P_{I,k(X)}^{d}$ is the probability of growth of land use type k on the spatial unit i.

The CA Model based on Muti-type Random Patch Seeds (CARS)

CARS is a scenario-driven land use simulation model based on Cellular Automata (CA). It mainly simulates the land use distribution pattern by obtaining the development probability of each land use type. The formula for the total probability of conversion for land use type k is as follows:

$$P_{0,i,k}^{d=1,t}=P_{i,k}^{d=1}\times\Omega_{i,k}^{t}\times D_{k}^{t} \tag{S5}$$

In formula (S5), $P_{0,I,k}^{d=1,t}$ is the total probability of conversion for land type k; $P_{I,k}^{d=1}$ is the probability of growth of land use type k on the spatial unit i; $\Omega_{I,k}^{t}$ is the neighborhood weight of the spatial unit i, which is the proportion of land use type k in the neighborhood. D_k^t is the effect of land use type k on future demand. It is an adaptive driving factor that depends on the gap between the amount of land use and demand at period t after iteration of land use type k. The formulas of $\Omega_{I,k}^{t}$ and D_k^t are as follows:

$$\Omega_{i,k}^{t}=\frac{con\left(c_i^{t-1}=k\right)}{n\times n-1}\times w_k \tag{S6}$$

$$D_k^t=\begin{cases} D_k^{t-1}\left(\left|G_k^{t-1}\right|\leqslant\left|G_k^{t-2}\right|\right) \\ D_k^{t-1}\times\dfrac{G_k^{t-2}}{G_k^{t-1}}\left(G_k^{t-1}<G_k^{t-2}<0\right) \\ D_k^{t-1}\times\dfrac{G_k^{t-1}}{G_k^{t-2}}\left(0<G_k^{t-2}<G_k^{t-1}\right) \end{cases} \tag{S7}$$

In formulas (S6) and (S7), con is the total number of grid units occupied by the land use type k in the last iteration in the n-by-n window; w is the weight between different land use types, and the default value is 1; G_k^{t-1} and G_k^{t-2} are the differences between the current and future demand for land use type k in the t-1 and t-2 iterations, respectively.

Accuracy verification

Confusion matrix for land use classification accuracy verification on 2020 (Table S3).

Table S3. Confusion matrix accuracy verification on 2020.

	Ground Truth Pixels						
Type	CL	FL	GL	WA	COL	UL	Total
CL	26321	302	796	232	1493	9	29153
FL	264	28724	1054	27	66	7	30142
GL	969	845	19941	81	35	21	21892
WA	345	24	57	1357	16	8	1807
COL	1346	178	57	12	6885	0	8478
UL	1	9	3	0	0	82	95
Total	29246	30082	21908	1709	8495	127	91567
	Commission Error (CE) and Omission Error (OE)						
Type	CE Percent (%)				OE Percent (%)		
CL	9.71				10.00		
FL	4.70				4.51		
GL	8.91				8.98		
WA	24.90				20.60		
COL	18.79				18.95		
UL	13.68				35.43		
	Producer's Accuracy (PA) and Use's Accuracy (UA)						
Type	PA Percent (%)				UA Percent (%)		
CL	90.00				90.29		
FL	95.49				95.30		
GL	91.02				91.09		
WA	79.40				75.10		
COL	81.05				81.21		
UL	64.57				86.32		
	Overall Results						
Overall Accuracy					90.9826%		
Kappa Coefficient					0.875451		

Note: Cultivated Land (CL); Forest Land (FL); Grassland (GL); Construction Land (COL); Water Area (WA); Unutilized Land (UL).

InVEST model

The InVEST model mainly consists of four carbon pools, including Carbon of above-ground biomass (C-above), Carbon of below-ground biomass (C-below), Carbon of soil organic matter (C-soil), and Carbon of dead organic (C-dead). Based on the assumption that the carbon density of a given type is a constant that does not vary with time, the InVEST model can estimate the carbon storage of a specific region in combination with land use data. The calculation formula is as follows:

$$C_i = C_{i-above} + C_{i\text{-}below} + C_{i\text{-}soil} + C_{i\text{-}dead} \quad \text{(S8)}$$

$$C_{total} = \sum_{i=1}^{n} C_i \times S_i \quad \text{(S9)}$$

In formulas (S8) and (S9), i is the ith land use type, Ci is the ith total carbon density (t/hm^2), $C_{i\text{-}above}$ is the ith above-ground biomass carbon density, $C_{i\text{-}below}$ is the ith below-ground biomass carbon density, $C_{i\text{-}soil}$ is the ith soil organic matter carbon density, $C_{i\text{-}dead}$ is the ith dead organic carbon density. C_{total} is the total carbon storage (t), n is the total number of land-use types, and S_i is the area of ith land use type (hm^2).

Land use transfer matrix from 1990 to 2020

Table S4. Land use transfer matrix between 1990 and 2000 (hm^2).

		2000						Total	Decrease
		CL	FL	GL	WA	COL	UL		
1990	CL	518775.03	978.48	21.87	1423.98	11935.35	0.00	533134.71	14359.68
	FL	114.21	486100.44	1670.22	17.01	1244.97	0.00	489146.85	3046.41
	GL	2118.15	42.93	355368.87	223.56	31.59	0.00	357785.10	2416.23
	WA	3559.14	63.18	904.77	22640.31	4.05	0.00	27171.45	4531.14
	COL	8.10	0.81	0.81	0.00	77473.26	0.00	77482.98	9.72
	UL	0.00	0.00	0.00	0.00	0.00	1809.54	1809.54	0.00
Total		524574.63	487185.84	357966.54	24304.86	90689.22	1809.54	1486530.63	
Increase		5799.60	1085.40	2597.67	1664.55	13215.96	0.00		

Table S5. Land use transfer matrix between 2000 and 2010 (hm^2).

		2010						Total	Decrease
		CL	FL	GL	WA	COL	UL		
2000	CL	463959.90	7479.54	15380.28	5510.43	32203.17	41.31	524574.63	60614.73
	FL	4847.04	467706.96	9802.62	528.93	4215.24	85.05	487185.84	19478.88
	GL	19831.23	17950.41	317077.74	1433.70	1535.76	137.70	357966.54	40888.80
	WA	4118.85	501.39	1152.63	18359.46	170.10	2.43	24304.86	5945.40
	COL	6746.49	265.68	394.47	138.51	83141.64	2.43	90689.22	7547.58
	UL	32.40	145.80	140.94	0.00	4.05	1486.35	1809.54	323.19
Total		499535.91	494049.78	343948.68	25971.03	121269.96	1755.27	1486530.63	
Increase		35576.01	26342.82	26870.94	7611.57	38128.32	268.92		

Table S6. Land use transfer matrix between 2010 and 2020 (hm^2).

		2020						Total	Decrease
		CL	FL	GL	WA	COL	UL		
2010	CL	445397.94	5313.60	14192.01	5484.51	29029.59	118.26	499535.91	54137.97
	FL	4261.41	471524.49	16613.10	412.29	1010.07	228.42	494049.78	22525.29
	GL	10095.84	10807.83	320822.37	1497.69	533.79	191.16	343948.68	23126.31
	WA	1962.63	322.38	773.55	22502.61	255.96	153.90	25971.03	3468.42
	COL	10515.42	2668.14	841.59	152.28	107090.10	2.43	121269.96	14179.86
	UL	36.45	103.68	127.17	2.43	1.62	1483.92	1755.27	271.35
Total		472269.69	490740.12	353369.79	30051.81	137921.13	2178.09	1486530.63	
Increase		26871.75	19215.63	32547.42	7549.20	30831.03	694.17		