https://doi.org/10.5194/essd-2025-222
Preprint. Discussion started: 3 June 2025

Open Access Earth System Science Data Discussions

Remapping Carbon Storage Change in Retired Farmlands on the Loess Plateau in China from 2000 to 2021 in High Spatiotemporal Resolution

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https://doi.org/10.5194/essd-2025-222
Preprint. Discussion started: 3 June 2025

Abstract: The soil organic carbon pool is a crucial component of carbon storage in terrestrial ecosystems, playing a key role in regulating the carbon cycle and mitigating atmospheric CO_2 concentration increases. To combat soil degradation and enhance soil organic carbon sequestration on the Loess Plateau, the Grain-for-Green Program (GFGP) has been implemented. Accurately quantifying carbon capture and storage (CCS) resulting from farmland retirement is essential for informing land use management. In this study, the spatial and temporal distribution of retired farmlands on the Loess Plateau was analyzed using Landsat imagery from 1999 to 2021. To assess the effects of the length of farmland retirement, climate, soil properties, elevation, and other factors on CCS, climate-zone-specific linear regression models were developed based on field-sampled soil data. These models were then used to map the dataset of CCS across the retired farmlands. Results indicate that a total of 39,065 km^2 of farmland was retired over the past two decades, with 45.61% converted to grasslands, 29.75% to shrublands, and 24.64% to forestlands. The length of farmland retirement showed a significant positive correlation with CCS, and distinct models were developed for different climatic zones to achieve high-resolution (30 m) CCS mapping. The total CCS from retired farmland on the Loess Plateau was estimated at 21.77 Tg in carbon equivalent according to the dataset, with grasslands contributing 81.10%, followed by forestlands (11.16%) and shrublands (7.74%).

Keywords: Length of farmland retirement; carbon capture and storage; ecological restoration; land use change; grain-for-green

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1. Introduction

Soil organic carbon (SOC), as the largest terrestrial ecosystem carbon pool, plays a crucial role in regulating climate change (Mir et al., 2023). Global SOC was estimated at approximately 1,400-1,500 Pg C, about four times the organic carbon pool of terrestrial plants (Scharlemann et al., 2014). The high SOC is essential to support multiple ecological benefits, such as purifying water, increasing crop yields and maintaining primary productivity (Paustian et al., 2019). Currently, 1/3 soil in the world is degraded, causing many socioeconomic (e.g., unemployment, poverty, immigration) and environmental (e.g., desertification, ecosystem degradation, biodiversity loss) issues (Ferreira et al., 2022; Ouyang et al., 2016). The large area of degraded soil also released more than 50 Pg carbon per year into the atmosphere which is conflict to the decarbonization target for mitigating global warming (Prăvălie et al., 2021). Therefore, the restoration of degraded soil is urgently needed for sustainable development and environment safety.

Ecological restoration by nature alone is a lengthy process. Under the urgent need for restoring degraded soils and mitigating climate change, scientific management measures are necessary to accelerate the ecosystem restoration (Lengefeld et al., 2020; Pape, 2022; Wang et al., 2021a). Many large-scale ecological restoration strategies around the world have showed encouraging ecological benefits. Brazil's Atlantic Forest Restoration Pact (AFRP) was established in 2009, and Argentina and Paraguay joined the impressive project in 2018, forming the Atlantic Forest Restoration Tri-national Network (Calmon et al., 2011). Hundreds of organizations have been actively involved in this decade-long efforts to protect and restore the forest, which recovered about 7,000 km² forest and enhanced regional biodiversity (De Oliveira Faria and Magrini, 2016). Forests established by restoration of the Brazilian Atlantic Forest between 2010 and 2015 would have sequestered 1.75 Pg carbon if they were not re-cut (Piffer et al., 2022). The Development Project "Green Great Wall" in Africa was launched by the African Union in 2007, aiming at restoring savannahs, grasslands and farmlands across Africa to help biodiversity cope with climate change and desertification. The goals of the project are to restore 1,000,000 km² in 2030 and sequester 250 Tg C (Graham, 2022; Macia et al., 2023). China has started ecological restoration practices and researches since the 1970s, and has implemented six national key ecological restoration projects (Cui et al., 2021). Among the projects, the GFGP is one of the most ambitious projects in the world with the highest investment and the largest implemented area (Xu et al., 2022). From 1999 to 2019, the GFGP implemented in 25 provinces and exceeded 0.343 million km² land area with 49 Tg sequestered carbon, indicating a significant potential of carbon capture and storage (CCS) by ecological restoration (Lu et al., 2018). Based on Deng et al.'s (2017)(Deng et al., 2017) study, the total carbon stock in the GFGP affected area was 682 Tg C in 2010, and projected to 1,697 Tg C in 2020.

One of the primary area of the GFGP is the Loess Plateau, because the long-term indiscriminate cultivation and logging on the Loess Plateau has caused over 40% of the total area (about 270,000 km²) in severe soil erosion and a significant loss of organic carbon (Shao et al., 2022). As the implementation of the GFGP, 96.1 Tg C was sequestered from 2000 to 2008 on the Loess Plateau (Feng et al., 2013; Xiao, 2014). Nonetheless, current estimations of CCS still have large uncertainties due to the technology and data limits (Zhang et al., 2022). On the Loess Plateau, the accumulation of SOC can be affected by many untested factors, such as ecosystem types and length of farmland retirement. Moreover, most of the studies fail to differentiate the carbon sequestration between retired and in use farmlands, and caused an overestimate of CCS. Therefore, a more reliable estimation should be reached to quantify the CCS of the retired farmlands with the consideration of those issues (Deng et al., 2017; Sun et al., 2016).

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Regarding to the complex spatial heterogeneity on the Loess Plateau and long-time implementation of the GFGP (Ma et al., 2022), the change of SOC in high resolution since the implementation of the GFGP is essential to clarify the CCS from large-scale ecological restoration, and can provide scientific guidance for ecological restoration policy and land use management on the Loess Plateau and sustainable utilization of vegetation resources. With the advancing of remote sensing technology and well-designed sample scheme, the objectives of this study are: 1) to identify the year-by-year retirement of farmlands on the Loess Plateau from 2000 to 2021; 2) to develop models of CCS for the retired farmlands contributed by the GFGP; 3) to map the CCS in 30 m resolution and estimate the total CCS from the retired farmlands on the Loess Plateau after the implementation of the GFGP.

2. Materials and Methods

2.1 Study Area

The Loess Plateau (100° 52 ′–114° 33′ E, 33° 41′ –41° 16′ N) is located in the north central part of China (Fig. 1-a), in the middle reaches of the Yellow River, with a sensitive and fragile ecological environment, belonging to the warm temperate continental monsoon climate, characterized by dry and cold in spring and winter, warm and hot in summer and autumn (Ma et al., 2022). The average annual temperature is 3.6–14.3°C. The average annual precipitation is 400–600 mm, of which is concentrated between July and September, and decreases from east to west and south to north (Zhou et al., 2016). The annual evaporation is 1,400–2,100 mm, with a trend of low in the south and east, high in the north and west. The elevation is 800–3,000 m, and the original surface vegetation mostly is grassland, shrubland, deciduous broadleaf forest, and mixed broadleaf-conifer forest (Zhou et al., 2016). The total area of the Loess Plateau is 635,000 km^2, including Shanxi, Ningxia, Shaanxi, Gansu, Qinghai, Inner Mongolia, Henan provinces. The main terrain is hilly and gully, with soft loessial soil texture.

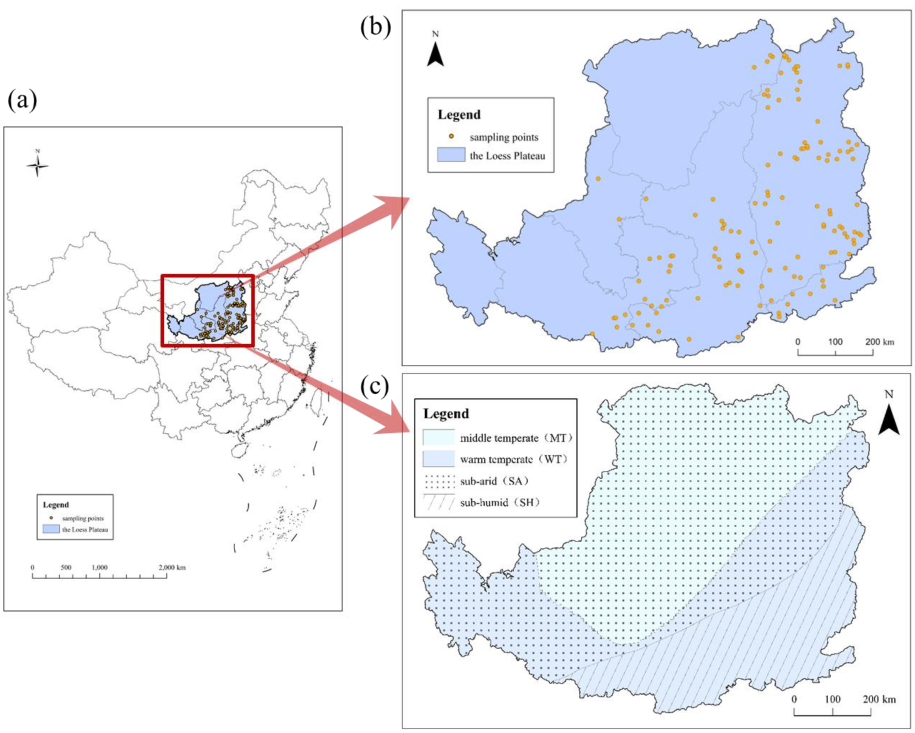

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Figure 1. The map of the study area, (a) location, (b) soil sampling sites and (c) climate zones.

2.2 Identifying Retired Farmlands

To identify and confirm the spatial range of the annual retired farmlands on the Loess Plateau, Landsat remote sensing images (30 m resolution) from 1999 to 2021 were downloaded from the United States Geological Survey (USGS, https://EarthExplorer.usgs.gov). The images with less cloud (lower than 10%) in growing season (from May to September) were selected for further analysis. Those images were processed by the standard steps recommended by ArcGIS Pro 2.8 (Environmental Systems Research Institute, Inc., ESRI), including preprocessing, image classification and validation. To improve image readability, remote sensing images were first preprocessed in ENVI 5.3, including radiometric calibration, FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) atmospheric correction, gram-schmidt pan sharpening, seamless mosaic and subset data from ROIs (regions of interest). The image classification was then performed in ArcGIS Pro 2.8. In this study, we used the support vector machine (SVM) supervised classification method to classify the land cover types into the following seven categories: farmland, forestland, grassland, shrubland, water body, building land, and bare land. The training samples were selected by visual interpretation and managed by training sample manager. In the accuracy validation stage, the kappa coefficients for the studied period were in a range of 0.76–0.90 and the overall accuracy were 0.80–0.91 for different land cover types.

2.3 Field Sampling and SOC Measurements

To determine the CCS of different ecosystems that established on retired farmlands, an initial set of sample sites were created evenly with 5 km gaps based on the spatial distribution maps of retired farmlands (Fig. 1-b), and the final sample sites were determined by removing unqualified sites with ultra-high spatial resolution images (0.5 m resolution). Finally, 2,430 soil samples from 135 sample sites were collected from fields. Nine soil samples (three 10-cm layers from top 30 cm soil in 3 sample points) were collected for every sample site, and nine soil samples from the nearest farmlands were also collected similarly. Each soil sample was individually bagged, labeled, and stored in cold storage for lab measurement. After drying and grinding through a sieve at 0.25 mm, SOC of each soil sample was measured by potassium dichromate external heating method. The difference in total SOC of the top 30 cm soil layer between retired farmlands and the nearest farmlands was defined as CCS that contributed by the GFGP.

2.4 Model Development and CCS Mapping on the Loess Plateau

CCS is influenced by both natural environmental conditions and human activities, leading to variations across different zones of the Loess Plateau. Therefore, we developed different models based on the relationships between CCS and variables such as length of farmland retirement, geographic location, elevation, soil bulk density (BD), temperature, precipitation, and 19 bioclimatic factors. Length of farmland retirement were obtained from the annual spatial distribution data in retired farmlands on the Loess Plateau (subsection 2.2). The data sources for climate information can be found in subsection 2.5. The 19 bioclimatic factors were derived by following the formula in WorldClim (https://worldclim.org/data/index.html). All the variables were extracted to the sample sites by the Kriging interpolation and prepared for model development.

Based on the factors introduced above, we combined correlation analysis, random forest and single-factor regression to select variables for multivariate linear models of CCS. In consideration of wide climatic range on the Loess Plateau and different possible response of CCS to the retirement factors among climatic conditions (Zhang et al., 2018), we divided the Loess Plateau into different climatic zones for different ecosystem types (e.g., forestland, shrubland, grassland) based on

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climate regionalization in China–Climatic zones and climatic regions (GB/T 17297-1998) and climate data (subsection 2.5). As Fig. 1-c shows, we obtained middle temperature zone (MT, < 8°C) and warm temperate zone (WT, > 8°C) by the annual average temperature, and semi-arid zone (SA, <400 mm) and sub-humid zone (SH, >400 mm) by annual precipitation. In addition, three combined climatic zones were obtained: MT-SA, WT-SA and WT-SH. A multivariate linear regression model was developed specifically for each ecosystem types in each climatic zone. Before regression analysis, diagnosis of multicollinearity is conducted, and the threshold is generally set at 10 to detecting correlations between the independent variables and identify those independent variables that were incorrectly included in the same regression model. The regression models were evaluated and validated by residual analysis, cross-validation, significance level (*p*-value), coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE).

Based on the results of model evaluation, the best fitted models were selected to estimate the overall CCS of retired farmlands on the Loess Plateau. With the final selected multivariate linear regression models, the CCS in the top 30 cm soil layer were mapped by raster calculation in different climatic zones and ecosystem types at 30 m resolution. And the total CCS on the Loess Plateau contributed by the GFGP was obtained by summing up the CCS in all the retired farmlands without reclamation within the study period.

2.5 Data Sources

The temperature and precipitation data to calculate the 19 bioclimatic factors were from the China Meteorological Data Service Center (CMDC, http://www.geodata.cn). Elevation data of every grid cell were from the Digital Elevation Model database (https://e4ftl01.cr.usgs.gov/MEASURES/). Soil properties were retrieved from Harmonized World Soil Database (HWSD, https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/), and the boundary of the Loess Plateau was downloaded from the Resource and Environment Science and Data Center (https://www.resdc.cn/). All the raster data were resampled to 30 m resolution.

3. Results

3.1 Distribution of Retired Farmlands

From 1999 to 2021, the final retired farmlands without reclamation on the Loess Plateau was 39,065 km^2 (Fig. 2 v). The final retired farmlands were less than the area by summing up yearly retired farmlands because of frequent reclamation. The area of retired farmlands in every year has been fluctuating throughout the study period with no significant trend (Fig 2 a-u, Fig. 3). The least amount of retired farmlands occurred in 2002 (28,003 km^2; 4.41% of the whole studied area), and the most was 78,653 km^2 in 2016 (12.39% of the whole studied area). The retired farmlands were converted to different ecosystem types, including forestlands, shrublands and grasslands. The ratios of different ecosystem types in every year were in the ranges of 10.65%–38.60%, 14.63%–47.70% and 17.02%–64.98% for forestlands, shrublands and grasslands, respectively

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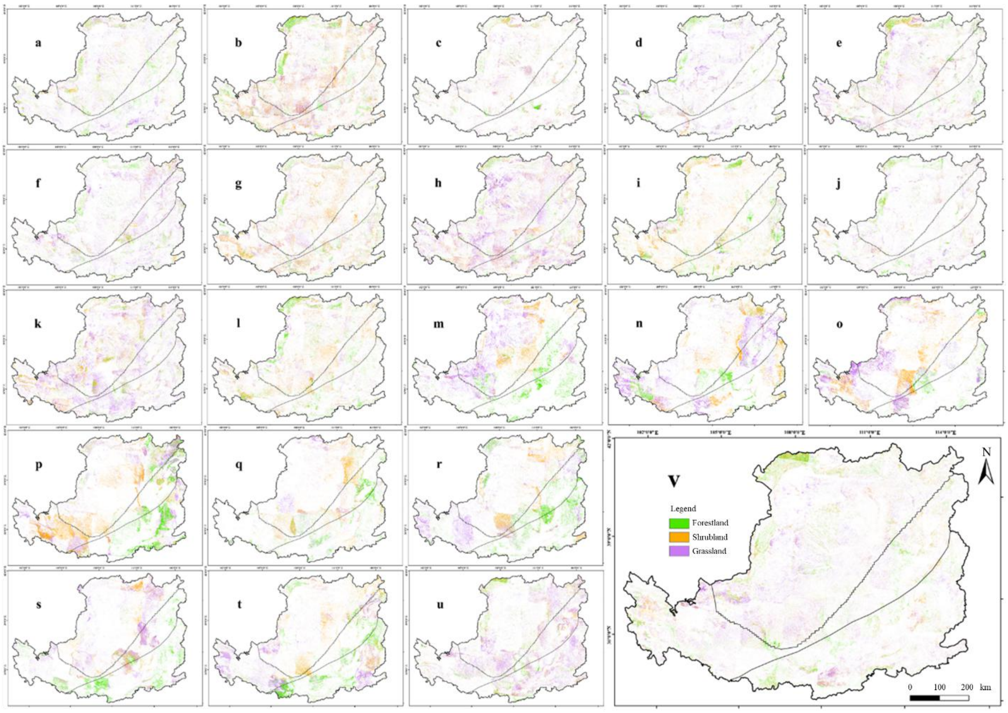
(Fig. 3). Within the studied period in average, most of the retired farmlands were converted to grasslands (45.61 %) and shrublands (29.75 %).

Figure 2. Spatial distribution of retired farmlands on the Loess Plateau from 1999 to 2021, (a) 1999-2000, (b) 2000-2001, (c) 2001-2002, (d) 2002-2003, (e) 2003-2004, (f) 2004-2005, (g) 2005-2006, (h) 2006-2007, (i) 2007-2008, (j) 2008-2009, (k) 2009-2010, (l) 2010-2011, (m) 2011-2013, (n) 2013-2014, (o) 2014-2015, (p) 2015-2016, (q) 2016-2017, (r) 2017-2018, (s) 2018-2019, (t) 2019-2020, (u) 2020-2021, (v) 1999-2021.



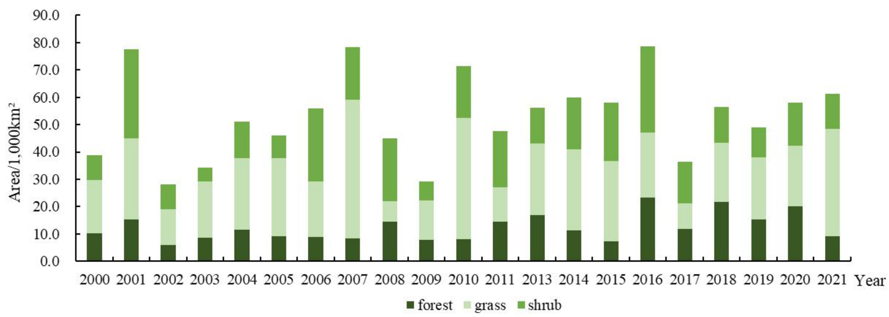


Figure 3. Area of different ecosystem types from retired farmlands from 2000 to 2021.

The retired farmlands were unevenly distributed among different climate zones (Fig. 2 a-v). For the final retired farmlands, the area in the middle temperate and semi-arid zone (MT-SA), warm temperature and semi-arid zone (WT-SA) and warm-temperature and semi-humid zone (WT-SH) were 20,299 km^2, 10,572 km^2 and 8,194 km^2, respectively. In the MT-SA zone, the dominant ecosystem type from retired farmlands was grasslands which had 9,705 km^2 (47.81%), and followed by shrublands (5,887 km^2, 29.00%) and forestlands (4,707 km^2, 23.19%). In the WT-SA zone, grasslands were also the dominant ecosystem type which accounted for 4,925 km^2 (46.59%), and forestlands accounted the least (2,384 km^2, 22.55%). In the WT-SH zone, the percentages of different ecosystem types were 30.96 %, 30.16 % and 38.88 % for

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forestlands, shrublands and grasslands, respectively.

Among different years (Fig. 2 a-u), the highest areas for each ecosystem type were forestlands in the WT-SH zone in 2016 (12,846 km^2), shrublands in the MT-SA zone in 2001 (15,441 km^2), and grasslands in the MT-SA zone in 2007 (26,171 km^2). The lowest areas were found in 2019 for forestlands in the WT-SA zone (813 km^2), in 2013 for shrublands in the WT-SH zone (271 km^2), and in 2013 for grasslands in the WT-SH zone (806 km^2).

Among provinces, the retired farmlands in different years had significant differences (Table S1), where Shanxi Province had the most in 2016 (30,912 km^2) and Qinghai Province had the least in 2017 (438 km^2). The final retired farmlands from 1999-2021 was the most in Inner Mongolia Province (8,626 km^2) and the least in Henan Province (739 km^2). More forestlands could be found in warmer and wetter regions. The largest forestlands (15,073 km^2) were found in Shanxi Province in 2016, while the least were found in Qinghai Province in 2016 (34 km^2).

3.2 Analysis of Soil Samples

The results of soil samples showed that the SOC were 2.19–62.70 g C/kg in retired farmlands, and 2.25–63.83 g C/kg in adjacent farmlands. The average SOC were the highest in forestlands (4.84–62.70 g C/kg), followed by shrublands (2.62–54.72 g C/kg) and grasslands (2.19–21.83 g C/kg). To facilitate the CCS estimation by area, we converted the SOC to area based content by soil bulk density. The highest value of CCS after retirement was from forestlands in the SH zone (26.52 kg C/m^2) and the lowest value was from sample in grasslands in the WT zone (0.91 kg C/m^2). Forestlands and shrublands had significantly increased the SOC by 48.53% and 20.34%, respectively ($p<0.05$, Fig. 4 a). Among different climatic zones (Fig. 4 b), forestlands in the SA zone had the biggest increase (58.80%), and followed by forestlands in the SH zone (44.53%) and shrublands in the MT-SA zone (26.74%). The findings indicated that the farmland retirement had significantly increased the SOC storage.

The CCS of different ecosystem types in different climatic zones had significant relationship to the length of farmland retirement (Fig. 5). The CCS was negative in the first few years and significantly increased as the length of farmland retirement increases, except forestlands in the SA zone and shrublands in the MT-SA zone. Most of the relationships indicated constant increase in CCS except CCS in grasslands in the MT zone which had a saturation point after 15 years of retirement.

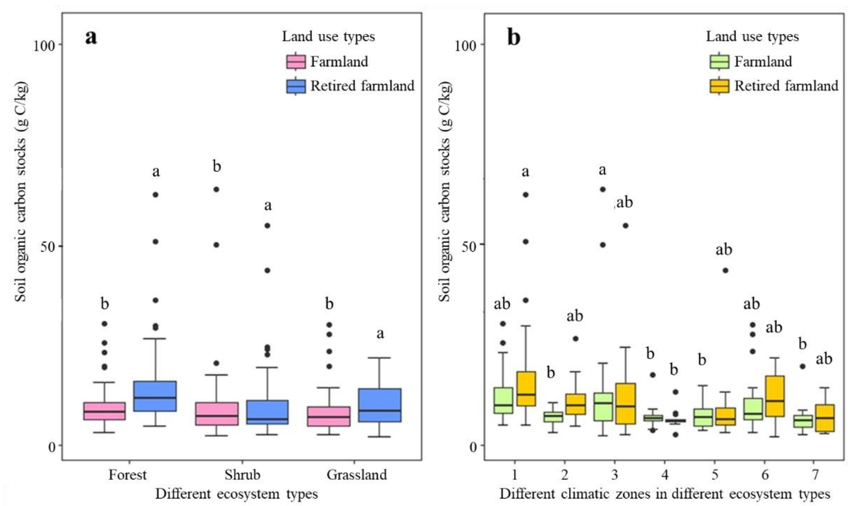

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Figure 4. SOC stocks in farmlands and retired farmlands (g C/kg), (a) Comparison of SOC stocks on the Loess Plateau in farmlands retired to different ecosystem types (forestland, shrubland, grassland) with those in adjacent farmlands, and (b) Comparison of different climatic zones are emphasized, and 1-7 represent the climatic zones of the different ecosystem types, i.e., forestlands in the SH zone, forestlands in the SA zone, shrublands in the WT-SH zone, shrublands in the WT-SA zone, shrublands in MT-SA the zone, grasslands in the WT zone, and grasslands in the MT zone.

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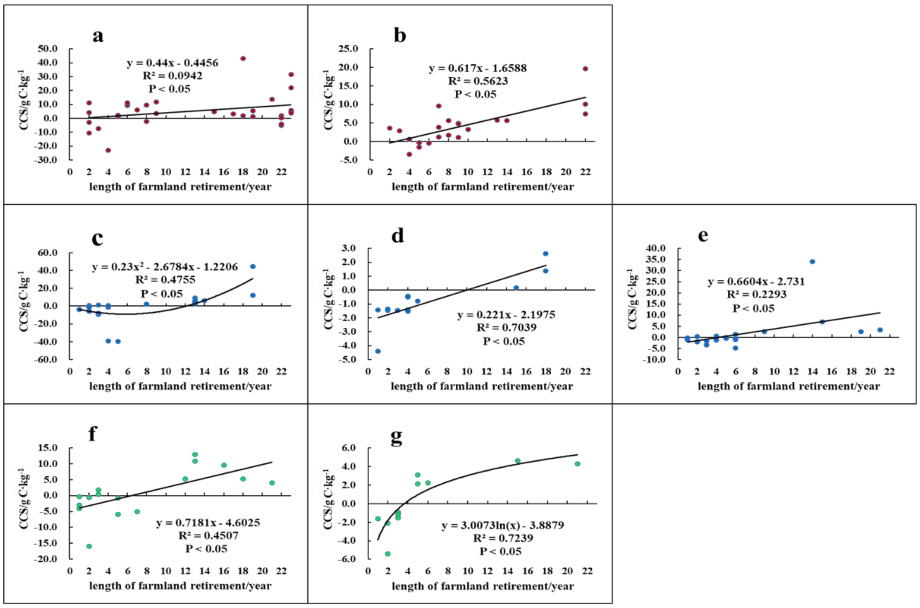

Figure 5. Relationship between length of farmland retirement and CCS, (a) forestlands in the SH zone, (b) forestlands in the SA zone, (c) shrublands in the WT-SH zone, (d) shrublands in the WT-SA zone, (e) shrublands in the MT-SA zone, (f) grasslands in the WT zone, (g) grasslands in the MT zone.

3.3 Models of CCS

3.3.1 Correlation analysis and variable importance

The critical variables for model development were selected by the Pearson correlation analysis and variable importance through package *randomForest* in R. The length of farmland retirement and CCS (Fig. 6 a) showed a significant positive correlation. Most of the environmental factors such as soil bulk density and bioclimatic factors had a weak negative correlation with CCS. Variable importance (Fig. 6 b) was measured in %IncMSE (percent increase in mean squared error) and IncNodePurity (increase in node purity). The combination of the two metrics illustrated that the length of farmland retirement on the Loess Plateau is the most important variable for CCS.

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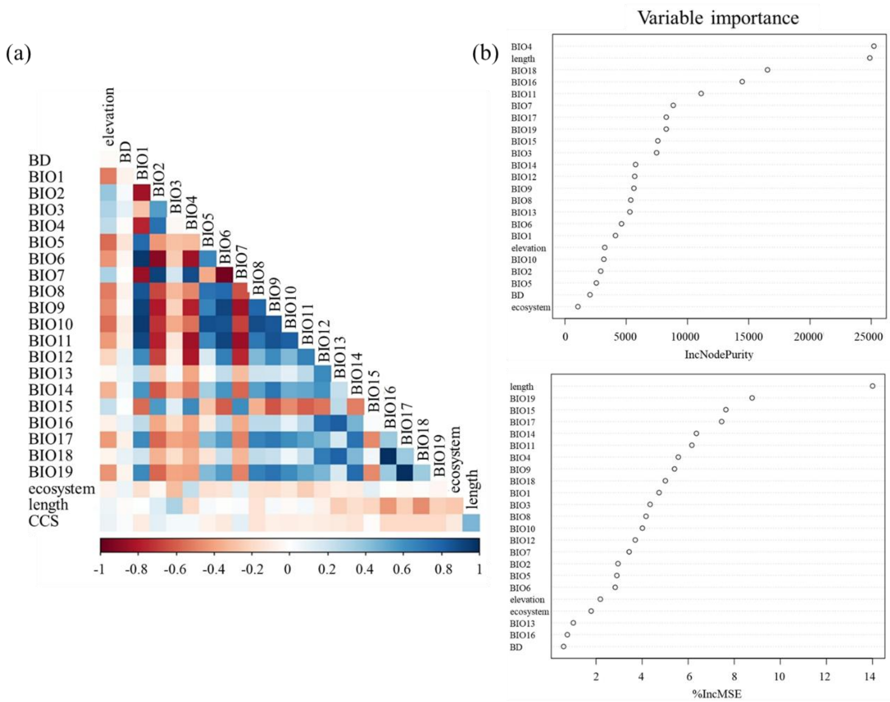

Figure 6. Correlation matrix (a) and variable importance (b) of CCS and environmental factor parameters.

3.3.2 Model development

Based on the results from correlation analysis and variable importance, all the factors significant contributing to the variance of CCS were introduced into the regression model. Samples for different ecosystem types were divided by different combinations of climatic zones to find the optimal model by Backward Stepwise Regression. The final models of CCS in different ecosystem types were shown in Table 1. In this table, *t* is the length of farmland retirement, *lat* is latitude, *ele* is elevation, *BD* is soil bulk density, and *BIO*1-*BIO*19 are 19 bioclimatic factors.

The analysis showed that seven regression equations were the best representative for the CCS on the Loess Plateau when the study area was divided into SH and SA zones for forestlands, WT-SH, WT-SA and MT-SA zones for shrublands, and WT and MT zones for grasslands. The coefficients of determination (R^2) ranged from 0.476 to 0.830 with p<0.05. The models with the highest R^2 were obtained for grasslands (0.830 in the WT zone and 0.790 in the MT zone), and the model with the lowest R^2 was for shrublands in the MT zone (0.476).

Table 1 Models of the CCS in retired farmlands on the Loess Plateau.

Ecosystem	Zone	Model	R^2	p-value	RMSE	MAE

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Forestland	SH		y_1=0.3195 t+14.95 lat+ 0.01356 ele − 0.00755 $BIO4$ − 4.02 $BIO5$+11 $BIO10$+ 0.44 $BIO13$+1.791 $BIO14$ − 23.81 $BIO15$ − 1.686 $BIO17$-632	0.605	<0.05	21.831	17.209
	SA		y_2=0.7384 t − 0.4148 $BIO12$+ 4.2594 $BIO14$ − 0.8341 $BIO17$+ 0.1456 $BIO18$+1.1633	0.618	<0.01	9.039	7.001
Shrubland	WT	SH	y_3=0.23 t^2 − 2.678 t − 1.221	0.476	<0.01	34.814	22.858
		SA	y_4=0.1555 t − 1.4904 $BIO1$ − 0.1544 $BIO17$+15.3573	0.773	<0.01	2.281	1.715
	MT	SA	y_5=1.6059 t − 12.1498 $BIO3$+ 0.0071 $BIO4$+0.7615 $BIO13$ − 1.2096 $BIO16$+523.89	0.551	<0.05	48.965	36.664
Grassland	WT		y_6=0.5457 t+31.412 BD+ 4.463 $BIO9$ − 2.489 $BIO11$ − 2.238 $BIO14$+27.184 $BIO15$ − 72.97	0.830	<0.01	8.659	7.112
	MT		y_7=-0.0497 t^2+1.455 t − 4.84	0.790	<0.01	4.114	2.898

3.4 Mapping CCS

According to the regression models for CCS and the distribution of retired farmlands, the CCS in the retired farmlands on the Loess Plateau was calculated (Fig. 7 a). The total benefit in CCS on the Loess Plateau was 21.77 Tg C with a range between -26.52 and 31.91 kg C/m^2 at 30 m raster level. The potential CCS by different ecosystem types changed significantly (Fig. 7 b, Table 2). Grasslands contributed the most CCS increment (17.657 Tg C). Among the different climatic zones for grasslands, MT zone contributed the most (78.04%, -0.48–3.04 kg C/m^2), followed by WT zone (21.96%, -8.20–31.91 kg C/m^2). Forestlands contributed the second largest CCS (2.429 Tg C) with 151.96% from SH zone (-26.52–22.86 kg C/m^2), and -51.96% from SA zone (-2.96–8.67 kg C/m^2). The shrublands only contributed 7.74% of the total benefit of carbon storage (1.685 Tg C) with 78.04% from MT-SA zone (-26.49–30.57 kg C/m^2), 45.07% from WT-SA zone (-4.00–3.28 kg C/m^2) and -23.11% from WT-SH zone (-4.60–26.10 kg C/m^2).

The potential CCS by different provinces also changed significantly, but the potential CCS in different ecosystem types by the same provinces were evenly changed (Table S3). CCS increased more in Shanxi and Shaanxi provinces, followed by Henan, Gansu, Inner Mongolia and Ningxia, and less in Qinghai province.

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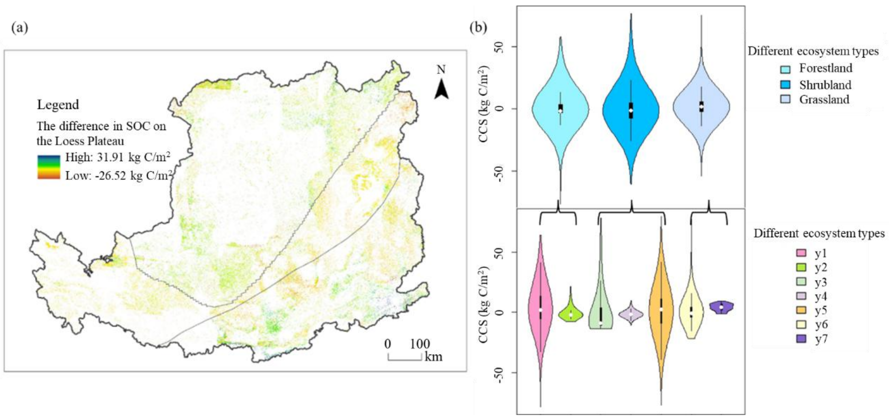

Figure 7. Spatial distribution of the CCS, (a) the distribution in the whole study area, and (b) raster level frequency of CCS.

Table 2 The CCS (positive and negative portion) in retired farmlands in different ecosystem types in different climatic zones (Tg C).

zone / type	MT-SA		WT-SA		WT-SH		Total by ecosystems
Forestland	1.318	-2.255	0.627	-0.952	6.461	-2.770	2.429
Shrubland	8.502	-6.223	0.369	-1.563	4.868	-4.269	1.685
Grassland	14.543	-0.765	13.196	-5.239	3.545	-7.625	17.657
Total by zones	24.363	-9.243	14.193	-7.753	14.874	-14.664	21.770

4. Discussion

4.1 Distribution of Retired Farmlands

In consideration of the topographic complexity and vegetational variation on the retired farmlands, a large-scale retrieve of retired farmland information from remote sensing images is challenging (Wei et al., 2021). For instance, farmlands and grasslands have similar spectrum characteristics in spring and summer seasons and can be easily confounded (Estel et al., 2015), which lead to inaccuracy in remote sensing image classification. The inaccuracy can be minimized by comparing with multi-source high-resolution remote sensing images (Yan et al., 2023). In this study, although different vegetation types were involved on the retired farmlands (e.g., forestland, shrubland and grassland), the accuracy in identifying retired farmlands could high to 90% by combining visual interpretation of Landsat dataset, field observation, globeland30 database, and ultra-high resolution images from Google Earth.

Farmland retirement is the main land use change driver on the Loess Plateau. As classified in this study, retired farmlands on the Loess Plateau from 2000 to 2021 are unevenly distributed across different climatic zones, because of the significant hilly and gully terrain in the study area (Huang et al., 2007; Wen et al., 2015). We focused on forestlands, shrublands and grasslands from retired farmlands, and noticed that most forestlands were distributed in the SH zone due to higher precipitation than the SA zone. Grasslands were more distributed in the MT zone than in the WT zone, due to the temperature in the MT zone being more favorable for grasses than in the WT zone, and people may be more engaged in

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pastoral activities in the WT zone. Shrublands were more distributed in the MT-SA zone than in the WT-SH zone because the WT-SH zone is more suited to forest growth, thus having high percentage of tree cover and relatively low distribution of shrub. In this study, grasslands accounted for a large proportion in retired farmlands on the Loess Plateau, but the increase in forestlands were more significant. Different patterns of retired farmlands among different years were mainly caused by policy orientation and farmers' willingness of participation. Within the studied period, the central government of China implemented two rounds of GFGP in 1999-2013 and 2014-present, respectively. High rates of retirement were observed at the beginning of every round due to promising subsides. The farmers' willingness of participation reduced thereafter, and a significant number of farmers chose to reclaim the retired farmlands (Xie et al., 2023).

4.2 Model development for CCS

Land use change due to GFGP can strongly affect SOC, and SOC tend to be lower in farmlands (Deng et al., 2014), which was proved in this study by comparing retired and adjacent unchanged farmlands. The benefits of CCS in the retired farmlands reveals a close relationship to the length of farmland retirement, although a slightly decease of SOC may be observed in early stage of retirement due to land use change (Deng et al., 2017). Although in the studied period, all the vegetation types had constant increasing trend after the first few years, the upper limit will be reached when the ecosystem become mature and stable, as showed in grassland with a logarithmic relationship. Some retired farmlands with decreasing SOC were found, which could be explained by interchange of reclamation and retirement (Qiu et al., 2018), but the deeper mechanism is still need to be explored. Moreover, the high SOC in adjacent farmlands due to good agricultural practice could also offset the benefit of CCS from the GFGP (negative CCS was mostly found in farmland with high SOC).

Based on the statistical analysis (Fig. 4), the range of the CCS in grasslands was significantly smaller than that in forestlands and shrublands. This indicates the accumulation rate of SOC in grasslands was lower than that in forestlands and shrublands due to the low primary productive and the fine quality of grass litter for decomposition (Lukina et al., 2020), whereas woody litter contains more lignin and decomposes slowly (Xiao et al., 2022). Therefore, different models were developed according to vegetation types and climatic zones. Based on the models, the climate factors had significant effect on CCS besides the length of farmland retirement. Among the climatic factors, the models showed that CCS were more sensitive to precipitation-based bioclimatic factors (e.g., *BIO*12-*BIO*19). This is because most of the Loess Plateau is located in semi-arid and arid area with limited precipitation (Zhang et al., 2015). Moreover, increased precipitation and temperatures can enhance the decomposition of surface litter (Sharma and Sharma, 2022), and in turn reduce CCS.

4.3 Benefits in CCS on the Loess Plateau

Under climate change, ecological restoration is an urgent need to improve the healthiness of degraded ecosystems (Liu et al., 2023; Yang et al., 2023). As a major benefit from ecological restoration, the increase in SOC (CCS) brings a lot of interests due to SOC is the major carbon pool in the ecosystems. To illustrate CCS from ecological restoration, only a comparison of restored and adjacent unrestored ecosystems should be persuasive (Francaviglia et al., 2019). Numbers of studies focusing on CCS in retired farmlands has been conducted on the Loess Plateau, and found an increasing CCS as a result of GFGP (Wang et al., 2021b), and the national SOC sequestration caused by retirement was estimated to be 14.46 Tg per year (Zhao et al., 2013). But they failed to make comparison with the adjacent farmlands. In this study, we analyzed the CCS of retired farmlands and adjacent in-use farmlands, and confirmed that the GFGP can provide significant amount of CCS on the Loess Plateau, although negative CCS was found in some areas.

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Recently, studies have shown that SOC stocks in the GFGP region on the Loess Plateau increased by 20.18 Tg C between 1982 and 2017 (Li et al., 2022). The total CCS (21.77 Tg C) of retired farmlands on the Loess Plateau estimated in this study was slightly higher than that value, which proved that the results of this study are reliable. Although the mechanisms of CCS are different for different vegetation restoration types in different climatic zones, the rate of carbon sequestration was higher in warm and humid areas than in cold or arid areas because of high temperatures and sufficient precipitation-induced strong photosynthesis and rapid plant growth. However, long time carbon storage in soil is essential in mitigate climate change. The high turnover rate of SOC in warm and humid areas may limit the benefit in carbon storage than in arid and semi-arid regions (Sierra et al., 2017).

4.4 Limitations and Uncertainties

Remote sensing images are widely used in studies of land use change because of their accuracy and timeliness. In this study, the use of Landsat dataset has practical feasibility to provide reliable distribution of retired farmlands. However, the Loess Plateau has a large spatial area, and has a fragmented and complex topography, which increases the difficulty of land use classification. Therefore, the 30m resolution image can result in misclassification, although we obtained acceptable accuracy (80%–91%). Recently, the availability of ultra-high resolution images (sub-meter resolution) allows a more accurate classification, but lacks of long period records.

In this study, the direct comparison of retired farmlands and adjacent farmlands reflected a more persuasive CCS. The multivariate linear regression models that developed for estimating CCS can reduce the estimation error in the consideration of the spatial heterogeneity on the Loess Plateau. However, to predict the future potential of soil carbon sequestration in the retired farmlands on the Loess Plateau, the assistant of process-based ecosystem models could be more reliable, such as DLEM (Dynamic Land Ecosystem Model, (Tian et al., 2003)), LPJ–GUESS (Lund Potsdam Jena General Ecosystem Simulator, (Smith et al., 2001)), and CENTURY (Parton et al., 1987)

5. Conclusions

Farmland retirement is an effective strategy to restore degraded ecosystem and increase carbon storage on the Loess Plateau. In this study, we found the total area of retired farmlands on the Loess Plateau during the study period was 39,065 km^2. The dominant ecosystem type was grasslands, followed by shrublands and forestlands. The area of retired farmlands showed significant interannual changes without a specific trend, and the retired farmlands varied in different climate zones. Area of retired farmlands in the MT-SA zone were significantly higher than WT-SA zone and WT-SH zone. Based on soil samples, we found that CCS increased with the length of farmland retirement, and developed seven regression models for CCS by length of farmland retirement, temperature, precipitation, soil bulk density, latitude and longitude, and ecosystem types. According to the models, the total benefits in CCS from retired farmlands on the Loess Plateau were estimated to be 21.77 Tg C, with the variation ranged from -26.52 to 31.91 kg C/m^2 at grid cell level. The most CCS were contributed by retired farmlands in the MT-SA zone (15.120 Tg C), followed by WT-SA zone (6.440 Tg C) and WT-SH zone (0.210 Tg C). Therefore, Long-term implementation of GFGP brought significant impacts on increasing soil carbon sinks on the Loess Plateau, which contributed significantly in mitigating climate changes and promoting sustainability in the studied area.

Competing interests

The authors declare no competing interests.

Data availability

https://doi.org/10.5194/essd-2025-222
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The associated datasets are available at Figshare (https://doi.org/10.6084/m9.figshare.28785971, Yang.,2025), including distribution of retired farmlands from 2000 to 2021, length of farmland retirement, and high resolution CCS from the retired farmlands.

Author contribution

BG: data curation, investigation, methodology, formal analysis, validation and visualization; MF: investigation, formal analysis and validation; LY: data curation; TG, CM, XH, ZG, ZM: resources and visualization; QL: funding acquisition and conceptualization; ZW: resources; WL: Conceptualization, methodology, project administration and supervision. BG and WL: Writing – original draft preparation; All authors: Writing – review & editing.

Acknowledgements

This study was funded by the National Key Research and Development Program of China (2022YFF1302200). The authors would like to thank all the reviewers who participated in the review.

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