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Substantial role of check dams in sediment trapping and carbon sequestration on the Chinese Loess Plateau

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Understanding the processes governing lateral terrestrial organic carbon transfer is confounded by the fact that organic carbon deposits on land have not yet been fully explored. Despite recent advances in understanding organic carbon deposition in aquatic ecosystems, the burial of organic carbon in dry depositional environments remains unclear. Here, combining large-scale field surveys and remote sensing techniques, we provide a robust estimate for sediment retention and organic carbon burial of check dams on the Chinese Loess Plateau. We find that the 50,226 active check dams have intercepted 10.2 ± 0.6 Pg eroded sediment during 1970-2020, which equals to 46% of the sediment load of Yellow River. Based on 86 deep sediment cores, we estimate that 21.6 ± 9.9 Tg of organic carbon was buried over the past 50 years by check dams with a burial rate of 468 ± 204 g C m^{-2} yr^{-1}, approximately one order of magnitude higher than that of global lakes/reservoirs. We also find that the organic carbon burial efficiency of check dams (~80%) is significantly higher than in other depositional environments. We argue that organic carbon burial by check dams represents a significant terrestrial carbon sink and must be accounted for in global carbon budget.

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The fate of lateral terrestrial organic carbon (OC) transfer remains highly controversial in the global carbon budget[1]. Soil-derived OC is not only passively transferred but also biogeochemically processed and sequestered in depositional areas[2]. It is reported that ~34–82% of the eroded OC is deposited in terrestrial depositional systems, constituting important terrestrial carbon sinks[3–5]. The latest compilation indicated that sediment and OC burial in terrestrial depositional environments are predicted to increase due to accelerated erosion and reduced sediment export fluxes caused by climate change and human activities[6]. Understanding the carbon fate in depositional areas is an important prerequisite for shedding light on the debate on whether the erosion-transport-deposition process is a net atmospheric C source or sink[7–9], and is critical to refining our knowledge of the carbon cycle[10].

Terrestrial depositional systems usually include dry depositional environments such as alluvial fans, floodplains, and check dams, as well as aqueous depositional environments such as reservoirs, lakes, and ponds[5,11,12]. Current research has focused primarily on reservoirs and lakes[3,12,13], while the burial of OC in dry depositional environments with higher sediment and OC storage remains poorly constrained[5,11,14]. Moreover, the carbon emissions of reservoirs and lakes are significantly higher than their carbon burial, and are usually regarded as important atmospheric carbon sources[3,12]. In contrast, the completely different OC properties and environmental characteristics of dry depositional systems may lead to the different fates of the buried OC, which deserves further exploration[11].

Check dams are widely distributed worldwide to control soil erosion and sediment losses, especially in arid and semi-arid areas with severe erosion[15,16]. As typical terrestrial dry depositional environments, check dams intercept large amounts of eroded sediment and associated OC[17]. Previous studies have paid particular attention to the hydrological, ecological, and geomorphological functions of check dams at the watershed scale[18–20]. However, there is still a lack of systematic studies to clarify the carbon burial and sequestration of check dams, which may lead to an underestimation of terrestrial carbon sequestration[11]. The Chinese Loess Plateau is a typical arid and semi-arid region in the world, with the most severe soil erosion and the densest distribution of check dams[21]. Since the 1970s, check dams have been widely promoted by the central government and local people as an effective way to control soil erosion and sediment loss on the Chinese Loess Plateau[17]. The construction of check dams contributes greatly to the sediment reduction of the Yellow River, which used to have the largest riverine sediment flux in the world but has undergone a substantial reduction of sediment by about 90% in recent decades (i.e., average annual load decreased from 1.8 Pg yr^{-1} before 1970 to 0.2 Pg yr^{-1} after 2000)[22]. The dry conditions and high sedimentation rates, coupled with the widespread distribution of check dams, make the Chinese Loess Plateau an ideal natural archive for studying OC burial and budget in terrestrial depositional environments[11]. Here we combine satellite and UAV remote sensing, as well as large-scale field surveys to quantify the sediment retention and OC burial in check dams, estimate the OC burial rate and efficiency, and determine the fate of the buried OC behind check dams. We find that check dams are hotspots of terrestrial carbon sinks and are worthy of further attention and application in arid and semi-arid regions around the world.

Results and discussion

Sediment trapped by check dams. Using an object-oriented classification method based on multi-source remote sensing data, we obtain the spatial distribution map (Fig. 1b) of check dams on the Chinese Loess Plateau (See Supplementary Note 1). A total of 50,226 existing check dams are identified, which silted farmland area of 93,100 hm^2 (Fig. 1b, c). The area of silted land of each check dam ranges from 0.01 to 625 hm^2 with an average of 1.8 hm^2, of which 50% is concentrated in 0.2–20 hm^2 (Fig. 2a). We then combine Unmanned Aerial Vehicle photogrammetry and virtual dam construction to establish an empirical formula to link the silted area to sediment volume (See methods and Supplementary Note 2). Based on measured bulk density data from the surface to the deep depth ($n = 60$), we further estimate the corresponding sediment mass of each check dam (See methods). The amount of sediment retaining mass of check dams varies between 0.01 and 5 million tons (Fig. 2b), of which 80% are <0.2 million tons. The existing 50,226 check dams intercept a total of 10.2 ± 0.6 Pg sediment, which equals ~46% of the Yellow River's sediment load to the Bohai Sea during the period 1970–2020 (Fig. 3a), indicating that check dams are a major contributor to the drastic sediment decline of the Yellow River. We then selected eight main tributaries of the Yellow River (i.e., Huangpuchuan, Tuweihe, Wudinghe, Qingjianhe, Yanhe, Beiluohe, Sanchuanhe, Xishuihe) to further quantify the sediment retaining effect of check dams. The results show that dense check dams reduced sediment load in the tributaries by 11–53% (Fig. 3b).

Carbon burial rates of check dams. We collect 2121 samples from 86 deep drillings or profiles on the Chinese Loess Plateau to evaluate the OC dynamics in the depositional environments (Figs. 4 and 5, Supplementary Table 1). The mean OC content of the check dam sediment is 0.22 ± 0.21% ($n = 2121$), significantly lower than previously reported in depositional areas worldwide[12,23,24]. Combined with the spatial distribution of OC contents obtained by Kriging interpolation (Fig. 5) and sediment mass of each check dam, we estimate that check dams on the Chinese Loess Plateau have collectively retained 21.6 ± 9.9 Tg OC (Fig. 6a and Supplementary Note 3). The corresponding OC burial rate is 0.43 ± 0.19 Tg C yr^{-1} (Fig. 6b), which is ~36% and 24% of the OC burial rate of the Chinese reservoirs (~1.21 Tg C yr^{-1}) (ref. [3]) and Chinese lakes (~1.80 Tg C yr^{-1}) (ref. [25]), respectively. If expressed as per unit area, however, the OC burial rate of check dams (468 ± 204 g C m^{-2} yr^{-1}) is significantly higher than that of global reservoirs (~169 g C m^{-2} yr^{-1}) (ref. [12]) and lakes (~24 g C m^{-2} yr^{-1}) (ref. [12]). Compared with other previously reported ecosystems with high C stocks, such as mangroves (~163 g C m^{-2} yr^{-1}) (ref. [26]) and fjords (~40 g C m^{-2} yr^{-1}) (ref. [27]), check dams are also substantially efficient in sequestering terrestrial OC (Fig. 6c).

Buried carbon and its fate. The deposition or burial of OC only represents the total amount of OC input into the depositional system. Only when the extent of OC preservation in the depositional environment (defined as OC burial efficiency) is considered can the actual carbon sequestration potential of the depositional area be reflected[28]. Based on the regression slope of OC content with depth in 86 sediment cores (Fig. 7), we estimate the OC burial efficiency of check dams to be ~80% ($n = 86$) (See methods), which is significantly higher than other typical depositional environments, such as reservoirs (~44%, $n = 36$)[29–32], lakes (~43%, $n = 35$)[33,34], colluvial and alluvial sediments (~18%, $n = 312$)[5,35–37], and marine sediments (~24%, $n = 82$)[38–40] (Fig. 8a).

High OC burial efficiency in check dams mainly depends on the intrinsic characteristics of the eroded OC[41]. Firstly, the OC content in check dam on the Chinese Loess Plateau is 0.22%

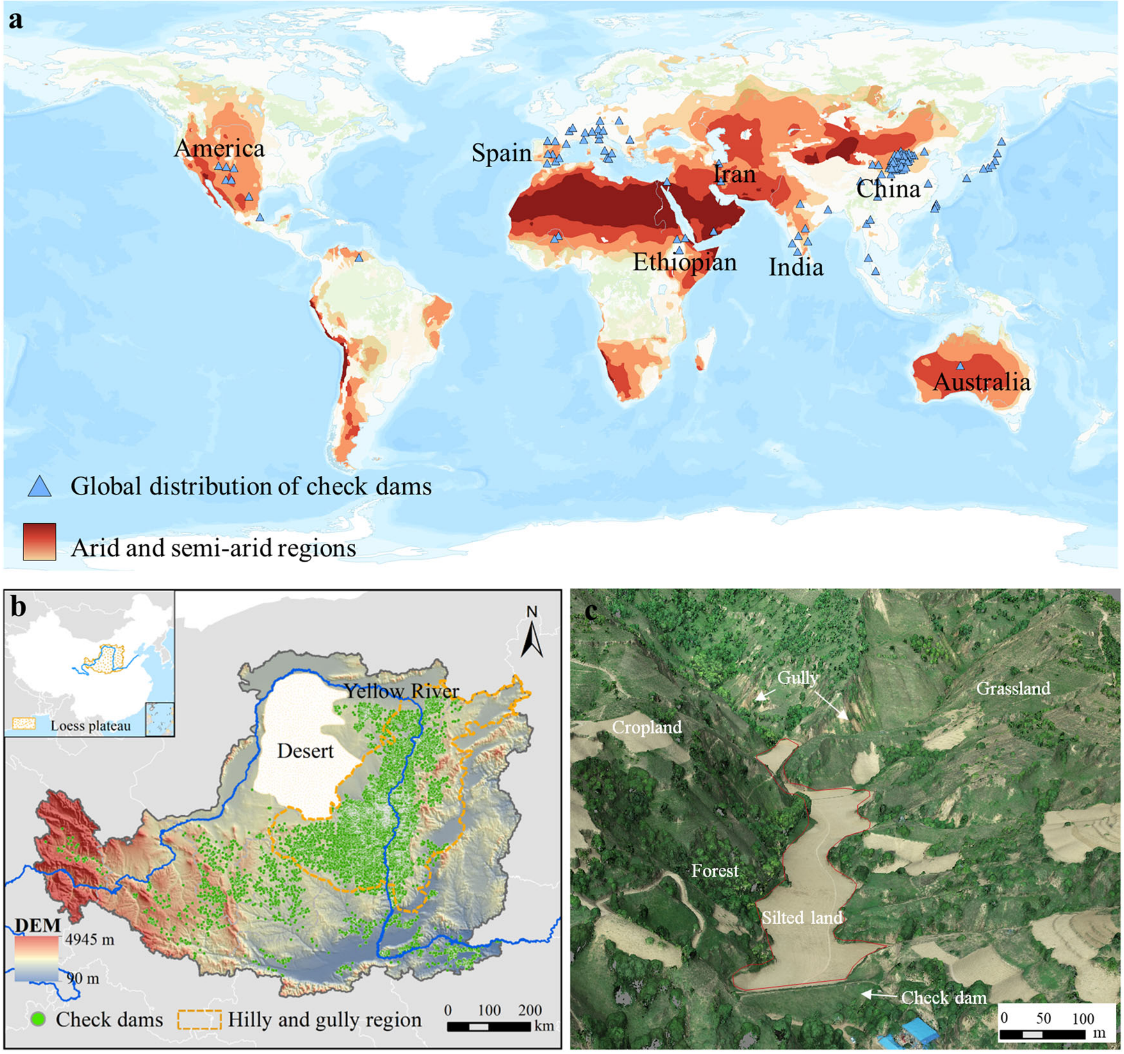

Fig. 1 Check dams in the world and the Chinese Loess Plateau. a Distribution of check dams in the world[16] (the blue triangle only represents the approximate spatial distribution of check dams around the world, not the actual number). **b** Distribution of check dams on the Chinese Loess Plateau. **c** Image of a typical silted land and check dam.

($n = 2265$), which is significantly lower than other reported depositional area worldwide[12,13]. The impoverishment of OC content is usually accompanied by low SOC decomposition potential[35]. Secondly, our radiocarbon isotope data indicate that the OC buried in the check dams is quite old, with an average radiocarbon age of 5509 ± 2679 yr BP ($n = 40$). Combined with the binary mixing model (See methods), we further find that the content of petrogenic OC was 0.07 ± 0.02% (Fig. 8b), which accounted for 29.9% of the buried OC in check dams. The linear trend shows that the mean $\Delta^{14}C$ activity of biospheric OC buried in the check dams is 0.76 ± 0.04 (Fig. 8b), and the corresponding radiocarbon age is 2205 yr BP. The mixture of the high percentage of petrogenic and pre-aged biospheric OC means that the OC buried in the check dams is highly recalcitrant[42]. Then, the significant positive correlation between the OC content and fine particles ($P < 0.01$, $n = 540$) (Fig. 8c) also shows that OC is more adsorbed by fine particles. Previous studies also show that OC buried in check dams consists mainly of a stable organic carbon pool combined with fine particles, of which mineral-associated OC accounts for 70% (ref. [43]) and microaggregate-associated OC accounts for 80% (ref. [44]). We further compare $\delta^{13}C$ and C/N ratio, two important indicators of OC degradation or mineralization, between the erosion area and the check dams (depositional area)[45]. We found no significant difference in $\delta^{13}C$ and C/N between the erosion area and the check dams (Fig. 8d), which may represent a low OC decomposition rate in check dams for several decades.

Additionally, the physical, chemical, and biological drivers of the depositional environment also significantly affect the OC burial efficiency. The dry, high bulk density and anoxia depositional environment of check dams have significantly reduced the biomass and activity of microorganisms, which further limited the decomposition of OC[17,46]. The low OC content coupled with the high recalcitrance in the dry depositional environment on the Chinese Loess Plateau has made it an efficient yet unquantified terrestrial carbon sink that has not been previously recognized.

Implications. The sediment retention and carbon burial of check dams analyzed in this study have at least three important implications for sediment and carbon management at regional and global scales. First, we have provided the most accurate estimate to date of the sediment retention of existing check dams on the Chinese Loess Plateau, and found that efficient sediment retention of check dams has resulted in an 11–53% reduction in sediment load to the Yellow River. These data will be beneficial to understanding the anthropogenic influences on the

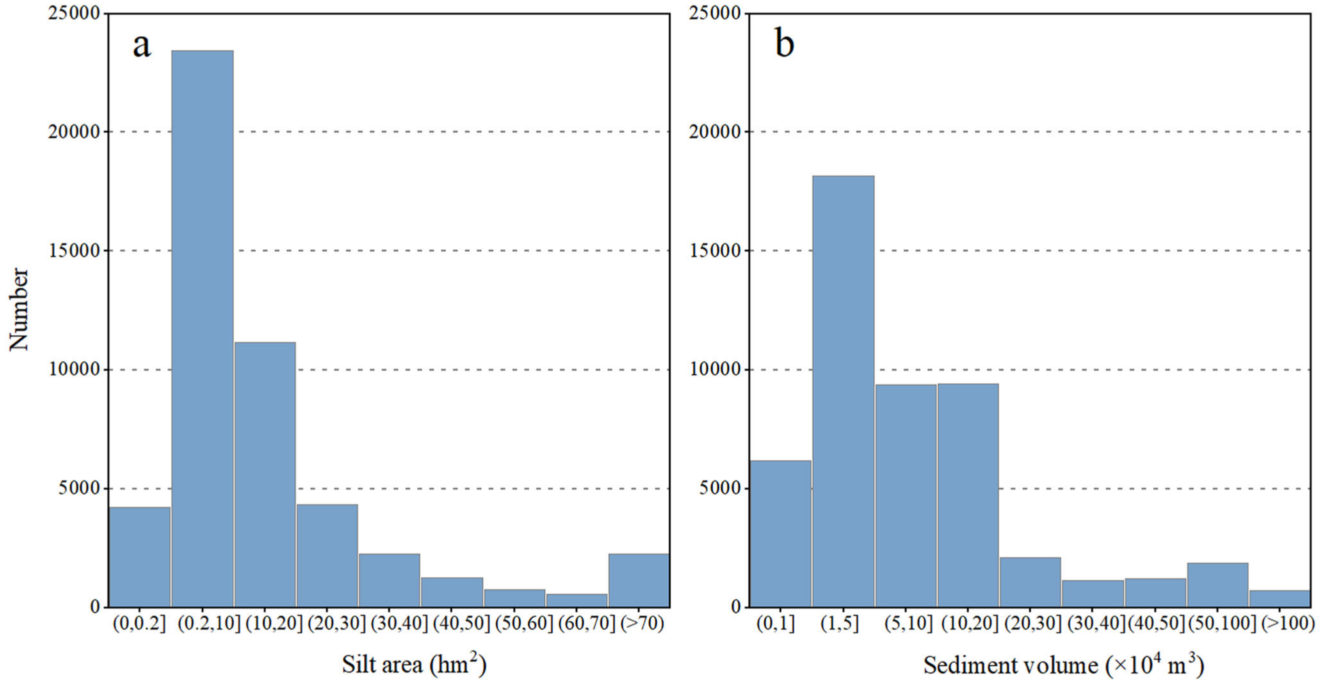

Fig. 2 Quantitative distribution characteristics of check dams on the Chinese Loess Plateau. **a** Frequency distribution of silted area. **b** Frequency distribution of sediment volume.

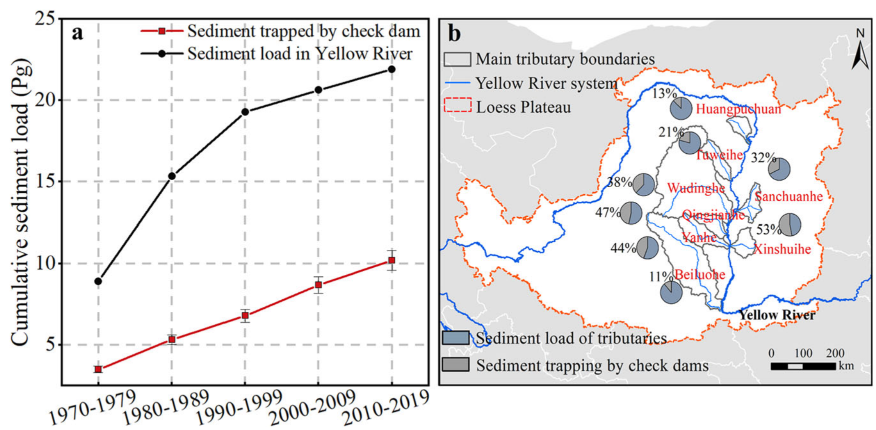

Fig. 3 Check dams trapped sediment. **a** Sediment trapped by check dams and sediment load of the Yellow River at different historical stages. Error bars represent standard deviation. **b** Sediment retention benefits of check dams in 8 main tributaries of the Yellow River. The river sediment load data is provided by the national basic hydrological station at the outlet of each basin, without error bars.

unprecedented changes in sediment reduction in the Yellow River and beyond[22]. According to the outline of the comprehensive management plan for the Chinese Loess Plateau, another 56,161 additional check dams will be built by 2030 (ref. [47]). Those built and planned check dams will further change the hydrological conditions of the Chinese Loess Plateau. Our study provides an important baseline for assessing the environmental influence of building check dams in the future.

Second, our results highlight that check dams are a substantial component of China's terrestrial carbon pool, possibly as important as reservoirs and lakes. It is noteworthy that check dams are more effective in terms of OC burial rate per unit area than lakes and reservoirs and other typical depositional environments. More importantly, inland water systems such as reservoirs and lakes are usually accompanied by stronger carbon emissions than carbon burial[12], which is usually represented as an atmospheric carbon source[48]. Conversely, check dams with dry depositional environments have higher OC burial rates and lower OC decomposition efficiencies, which is a hotspot of terrestrial carbon sink. Our analysis also indicates that check dams can considerably modify the carbon cycling associated with soil erosion processes. Check dams built at the low-order stream network can rapidly bury and effectively preserve the eroded OC and thus reduce the OC export flux from the Yellow River by 35–39% (refs. [4,49]). Furthermore, the rapid burial due to sediment deposition can also avoid further decomposition of OC by about 0.21 $\mathrm{Tg\,C\,yr^{-1}}$ during the long-distance fluvial transport according to the decomposition ratio (~48%) in this region[48]. Noticeably, our results show that large quantities of petrogenic OC have been buried in the check dams. Without the interception of these check dams, the decomposition of this eroded petrogenic OC during fluvial transport will represent an important carbon source on a geological time scale[17,50].

Third, we argue that the construction of check dams in global arid and semi-arid regions, such as Spain, Australia, America,

Fig. 4 Different sediment sampling methods. a–c Excavator, manual well digging, and well-drilling machine. **d** Flood couplets with clay and sand layer.

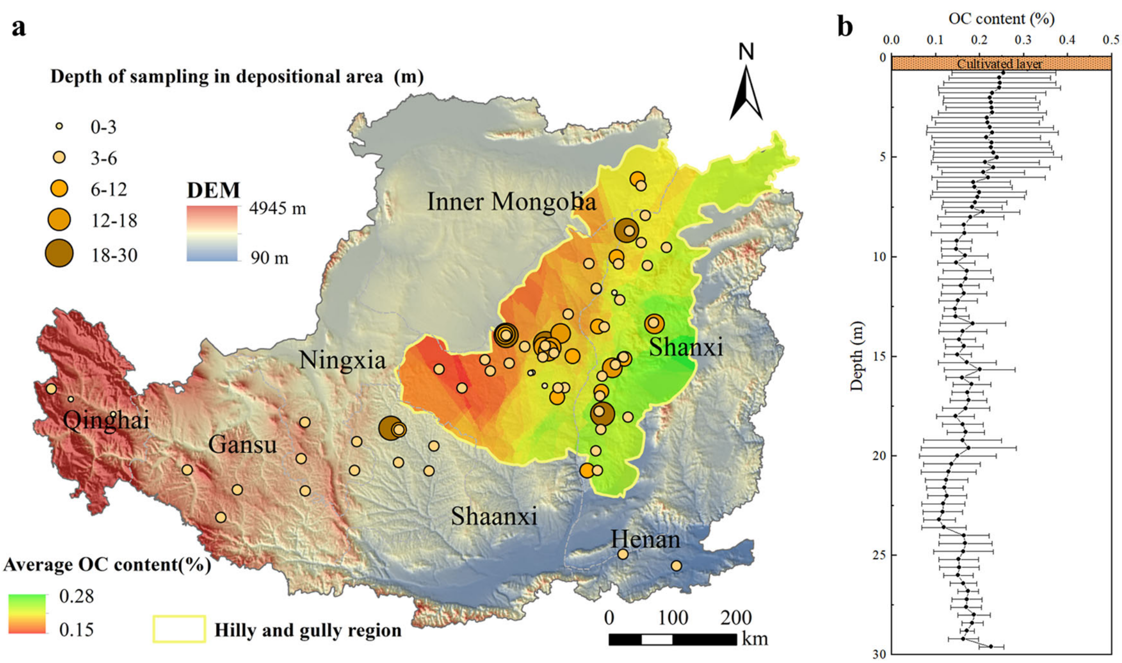

Fig. 5 Spatial and vertical distribution characteristics of carbon buried in check dams. a Spatial distribution of OC contents. Note: we only carry out Kriging interpolation in the hilly and gully region with the highest density of check dams and sampling points. (See Supplementary Note 3). **b** Average vertical distribution of OC content of all 86 deep sediment cores. Error bars represent standard deviation.

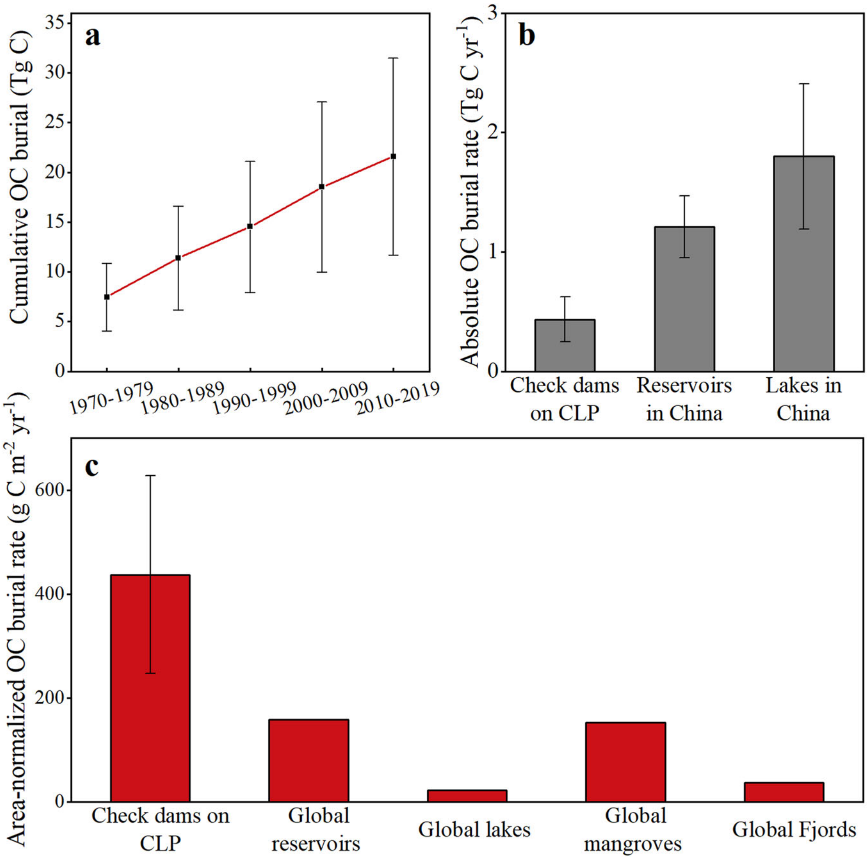

Fig. 6 Organic carbon (OC) buried behind check dams. a Cumulative buried OC of check dams on the Chinese Loess Plateau at different historical stages. **b** Absolute OC burial rates in typical terrestrial depositional environments in China. **c** Area-normalized OC burial rates in different depositional environments. Error bars represent standard deviation. Note: the error range is too large or not provided in the original references, so we do not show the error bar for other terrestrial depositional environments in Fig. 6c.

India, Iran, and Ethiopia (Fig. 1a), can contribute to a triple-win scenario of erosion reduction, carbon neutrality, and food security. Predictable global warming and increased human activities may aggravate soil erosion in these arid and semi-arid regions[51]. Check dams not only intercept eroded sediment, but also effectively preserve large amounts of OC during the deposition process. Additionally, the farmland formed by intercepting sediment will provide additional food production and carbon sequestration[52]. Overall, check dams provide unexpected synergies between multiple ecosystem services, thus providing a new potential solution for arid and semi-arid regions to achieve sustainable development goals 2, 13, and 15 in the 2030 Agenda for Sustainable Development[53]. This is particularly true when soil erosion, global warming, and food security are expected to further exacerbate in a human intensified near future[10,54].

Methods

Study area and fieldwork. The Chinese Loess Plateau covers an area of approximately 640,000 km^2, mainly within the middle reaches of the Yellow River, and is a major source of sediment for the Yellow River (Fig. 1b). The mean annual precipitation varies between 200 and 600 mm from the northwest to the southeast. Precipitation occurs mainly from June to September, in the form of high-intensity storms. The Chinese Loess Plateau suffers the most severe soil erosion due to deep erodible loess, fragmentary topography, intensive slope cropland, and arid to semi-arid climate. The Chinese Loess Plateau is sparsely vegetated and covered mainly by grassland ecosystems. Check dams have been one of the most commonly utilized structural measures for channel stabilization and erosion control in catchments on the Chinese Loess Plateau.

Fieldwork was carried out throughout the Chinese Loess Plateau during 2017–2021. We conducted field surveys at more than 400 dam-controlled catchments and ultimately selected 86 intact check dams for sampling (Supplementary Table 1). Sampling included the collection of representative samples of both the source materials of the dam-controlled catchments and check dam sediment. Each source sample consists of 10 subsamples collected from surface soils (0–5 cm depth) in a 5 × 5 m grid. Check dam sediment samples were collected using a variety of tools, including manual drill, impact drill, well-drilling machine, excavator, and manual well digging (Fig. 4). Because most of the check dams are located in the upper stream and with traffic inconvenience, we, therefore, choose the sampling method according to local conditions. We usually choose the center of the silted land as the sampling location. Vertical sampling was done at 25 cm intervals at depths above 600 cm, and we sampled every 50 cm at depths below 600 cm. Noticeably, since the check dams we selected are all planted with crops, sampling is usually carried out from 50 cm to reduce the influence of crops and their roots. Totally, we obtained 315 source samples and 2121 sediment samples throughout the Chinese Loess Plateau.

Experimental analysis of soil/sediment samples. Bulk density (BD) was obtained for 60 samples from 6 deep profiles. The maximum BD was 1.68 g cm^{-3}, and the BD sampling depth reached 11.3 m. A good linear relationship was found between sediment depth and bulk density (See Supplementary Note 2). We used BD at 1/2 depth due to the homogeneity and small variability of BD in loess sediments, and we assume that the sampled sediments are representative of the study area. The depth of each check dam was calculated based on the relationship between depth and silted area (See Supplementary Note 2). The particle size distribution was tested using a laser analyzer (Mastersizer 2000, Malvem, England). The concentration of OC and total nitrogen in the samples was measured using the $K_2Cr_2O_7$-H_2SO_4 oxidation method and Kjeldahl method, respectively, after passing through the 0.25 mm sieve[44].

The isotopic analyses were performed at the Beta Analytic Radiocarbon Dating Laboratory (Miami, USA). The $\Delta^{14}C$ activity was determined using accelerator mass spectrometry. The $\Delta^{14}C$ results were expressed as the fraction of modern carbon and as a conventional radiocarbon age (cal yr BP). For the measurement of stable carbon isotopes ($\delta^{13}C$), 2 g of sieved soil sample was pretreated with 10 ml H_3PO_4 solution for 12 h to remove the carbonate. The pretreated soil samples were combusted at 1020 °C and analyzed using the isotope ratio mass spectrometer (IRMS) (DELTA V Advantage, Thermo Fisher Scientific, Inc., USA). The $\delta^{13}C$ was reported in delta notation relative to the Vienna Pee Dee Belemnite (VPDB).

Fig. 7 Vertical distribution of OC concentration in 86 sediment cores. The shade areas represent 95% confidence interval and the blue and red mark represents a significant upward or downward trend, respectively ($p < 0.05$).

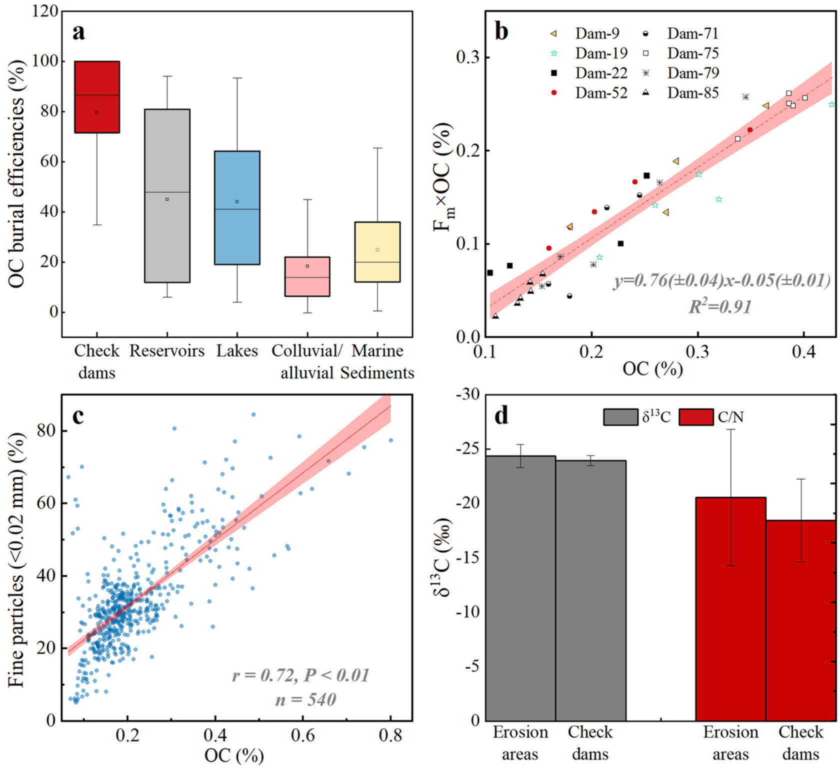

Fig. 8 OC burial characteristics of check dam. a OC burial efficiency of typical depositional environments including check dams ($n = 86$), reservoirs ($n = 36$), lakes ($n = 35$), colluvial/alluvial sediments ($n = 312$), and marine sediments ($n = 82$), respectively. The top and bottom of box chart is 75th and 25th percentile, the center of box is median, and the whiskers represent all samples lying within 1.5 times the interquartile range (IQR). **b** Scatter plot of modern carbon content (Fm × OC%, Fm: fraction of modern carbon) versus OC content for the sediment samples (See methods). **c** Relationship between OC content and fine particles. The red shade areas represent 95% confidence interval. **d** Differences in $\delta^{13}C$ and C/N between erosion area ($n = 45$ for $\delta^{13}C$ and $n = 65$ for C/N) and check dam (depositional area, $n = 149$ for $\delta^{13}C$ and $n = 2265$ for C/N). Error bars represent standard deviation.

Estimation of sediment retention, OC burial rate, and OC burial efficiency of check dams. We obtained the locations and silted areas of 50,226 check dams by combining high-resolution Google Earth images and an object-oriented classification method (Details See Supplementary Note 1). Then, we used Unmanned Aerial Vehicle photogrammetry and the virtual dam construction method to determine the relationship between silted area and sediment volume[55]. The sediment volume and mass of each check dam were estimated based on the area-volume empirical equation and measured bulk density (Supplementary Note 2).

We used the measured OC content of each depositional profile, combined with Kriging interpolation, to obtain the spatial distribution of OC content. Combing the total sediment mass of each check dam, we, therefore, estimated the OC storage of check dams (Supplementary Note 3). The Yellow River Water Resources Commission of the Ministry of Water Resources has provided the total amount and proportion of sediment trapped by check dams in different periods according to statistical data of grass-roots water conservancy departments[56]. Combined with this proportion and our estimated total sediment retention and OC burial of check dams (Supplementary Table 2), we roughly estimated the sediment retention rate and OC burial rate of check dams in different periods (Fig. 3a and Fig. 6a).

The burial depth of sediment and OC in check dam ranges from 3–30 m, corresponding to a burial time of 7–60 years. We simply estimated the OC burial efficiency based on the variation trend of OC content with burial depth (or burial time)[57]. We carried out regression analysis on 86 representative check dams, and the regression slope (S) represents the OC decomposition rate. We then determined the OC burial efficiency (OC_{be}) based on the decomposition of OC with burial depth (D) and the OC content of the topsoil sample ($OC_{topsoil}$).

$$OC_{be} = \left(1 - \frac{-S \times D}{OC_{topsoil}}\right) \quad (1)$$

Quantification of petrogenic OC and biospheric OC by binary mixing model. The sediment buried in the check dam is a mixture of erosion sediment from different sources (e.g., gully, cropland, and grassland). The buried sediment contains petrogenic OC (OC_{petro}) from bedrock and the ancient loess in the gully and biospheric OC (OC_{bio}) from pre-aged soil and modern plant debris in the sloping cropland/grassland. Based on the binary mixing model of radiocarbon isotopes[57], we quantify the petrogenic and biospheric OC in the sediment of check dams.

$$\%OC = \%OC_{bio} + \%OC_{petro} \quad (2)$$

$$Fm \times \%OC = \%OC_{bio} \times Fm_{bio} + \%OC_{petro} \times Fm_{petro} \quad (3)$$

$$Fm \times \%OC = \%OC \times Fm_{bio} - \%OC_{petro} \times (Fm_{bio} - Fm_{petro}) \quad (4)$$

As $Fm_{petro} = 0$, equation (4) can be simplified as:

$$Fm \times \%OC = \%OC \times Fm_{bio} - \%OC_{petro} \times Fm_{bio} \quad (5)$$

Where F_m, Fm_{petro}, and Fm_{bio} are the radiocarbon compositions of the total, petrogenic, and biospheric OC, respectively. Similarly, %OC, $\%OC_{petro}$ and $\%OC_{bio}$ represent the contents of OC, OC_{petro}, and OC_{bio}, respectively.

Every sample plotting on a straight line in a diagram representing the product %OC × Fm as a function of %OC is characterized by similar $\%OC_{petro}$. The content of petrogenic OC can be simply determined as the intersection between the trend and the *X* axis, and the mean $\Delta^{14}C$ activity of biospheric OC can be determined by the regression slope. More details can be found in Galy et al.[58].

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The following datasets were used in this study: digital elevation model (DEM) data were obtained from Shuttle Radar Topography Mission (SRTM) DEM with a resolution of 30 m (https://dwtkns.com/srtm30m/). The official statistics of the total amount and proportion of sediment trapped by check dams in different periods were obtained from the Yellow River Water Resources Commission of the Ministry of Water Resources[56]. The sediment load of the Yellow River and its tributaries were obtained from the Yellow River Sediment Bulletin 2021 (http://www.yrcc.gov.cn/zwzc/gzgb/gb/nsgb/). Geographic information and sampling information of 86 dam-controlled catchments in this study are available at Figshare (https://doi.org/10.6084/m9.figshare.22002578).

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Author contributions
N.F., Y.Z., and Z.S. conceived and designed the study. N.F. and Y.Z. wrote the paper. L.N. and C.L. analyzed the data. L.R., Z.W., Q.Y., and X.L. contributed discussion. X.Y. provided assistance with data analysis and software development. L.R., Z.W., X.L., Z.S., Z.G.W., J.J., and C.Y. commented and edited the manuscript.

Competing interests
The authors declare no competing interests.

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