Responses of carbon sequestration services to multiple soil and water conservation projects in Yanhe Basin, Loess Plateau

Jianxiang Zhang1, 2, 3, Yafeng Wang1, Jian Sun1, Junhe Chen1, Jingtian Zhang1, Dong Wang3, Huangyu Huo1, Eryuan Liang1

1 State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment (TPESRE), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

2 College of Earth and Environment Science, Lanzhou University, Lanzhou 730000, Gansu, China

3 Provincial Key Laboratory of Loess Engineering Properties and Applications, Key Disciplines of Civil Engineering, College of Civil Engineering, Longdong University, Qingyang 745000, Gansu, China

Corresponding Authors:

Yafeng Wang

yfwang@itpcas.ac.cn;

#### **Abstract**

Ecosystem carbon sequestration services (CSSs) are the most important ecosystem services (ESs) to mitigate global warming. Multiple soil and water conservation projects (SWCPs) have been implemented to restore disturbed ecosystems on the Loess Plateau, China. However, responses of CSSs to SWCPs are unclear due to trade-offs between CSSs and other ESs. Here, we quantified key ESs (i.e. carbon sequestration, water yield, soil conservation and crop production) and the spatio-temporal trade-off relationships by using RS/GIS techniques and ecosystem modeling in the Yanhe Basin, Loess Plateau, during 1990-2020. Additionally, the structural equation model (SEM) was used to estimate the direct and indirect inflences of multiple SWCPs including check dams, terraces and Grain for Green (GFG) on CSSs. Results show that CSSs has improved to 457 t/ha in 2020, which was twice compared to 1990. Here in, 57% of CSSs changes were explained by ESs and SWCPs. That is, water yield (-77%), soil conservation (76%), crop production (22%), GFG (80%), check dams (16%), and terraces (-72%), respectively. In order to balance trade-offs among ESs, GFG project with a focus on vegetation protection need to be prioritised, followed by check dams, and non-agricultural terraces such as [reverse-slope level terrace](http://search.ebscohost.com/login.aspx?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=10019332&asa=Y&AN=63484555&h=G6mLycMgNlOVPgRoCYkOUk10bJVLBylqio15fIxfweqCrJzP5PEtwMoYDxnyvIpHMRMXk%2BO8V2wSOuIGuR9DpA%3D%3D&crl=c)s and fish-scale pits. Our results provide a mechanistic understanding of how interacting processes of human activities at small catchments scales to influence carbon sequestration, and promote sustainable utlization of ESs in hill and gully regions of the Loess Plateau.

#### **KEYWORDS**

Ecosystem services, NPP, Check dams, Terraces, Grain for Green project, Yanhe Basin, Loess Plateau

#### **1 Introduction**

Carbon sequestration services (CSSs) are important ecosystem services (ESs) that can be expressed in terms of net primary production (NPP). CSSs can provide direct services such as wood, fiber and fuel, and indirect services of climate regulation (Liu et al., 2015; Lü, 2019). Natural or anthropogenic drivers effect CSSs directly or indirectly (MA, 2005). For example, large-scale drought has reduced global NPP in 2000s, while anthropogenic drivers such as the Grain for Green (GFG) project, had improved NPP substantially in many regions (Zhao & Running, 2010; Chen et al., 2015; Wang et al., 2017). In addition to the much-anticipated GFG project, there are some other important soil and water conservation projects (SWCPs) including check dams and terraces in the world (Abbasi et al., 2019). Effective soil erosion control represents a significant CSS (Ran et al., 2018). Therefore, responses of CSSs to different SWCPs urgently need to research. However, ecosystems simultaneously generate multiple services, which can lead to trade-offs among ESs (King et al, 2015). In order to balance trade-offs between different ESs, it is necessary to consider the interactions between CSSs and other key ESs.

In recent decades, most researchers have focused on the quantification of ESs and the trade-off relationship among ESs (Su et al., 2012; Zhang et al., 2020). For example, researchers have found trade-offs between NPP and other ESs, which can be quantified and identified by hot spots analysis (Zheng et al., 2016). However, a few researches have explored mechanisms driven by anthropogenic factors such as ecological restoration projects. For instance, ESs and trade-offs in karst area of China had changed dramatically driven by GFG (Wang et al., 2020). Moreover, the GFG program may intensify trade-offs between different ESs (Hu et al., 2021). GFG is just one of effective and large-scale SWCPs, while other projects such as check dams and terraces have implemented as early as 1970s, and are still being promoted vigorously, especially on the ecologically fragile Loess Plateau (LP) in China (Chen et al., 2022). There are about 110000 check dams in the LP, which have stored more than 2.1×1010 m3 sediments in recent decades (Wang et al., 2011). Scholars have demonstrated that reforestation without construction of check dams might result in decreasing of vegetation cover in the later years (Wang et al., 2021). Additionally, more than 260,000 km2 terraces had been constructed on the LP (Chen et al., 2022). Researchers have found that the LP ecosystem had shifted from carbon source to carbon sink under numerous SWCPs (Feng et al, 2013). Despite this knowledge, the interdependence effects of SWCPs factors in the mechanisms of that drive the dynamics in CSSs remain poorly understood.

The Yanhe Basin (YB) is a typical hill and gully region in the hinterland of the LP (Su et al., 2012). Moreover, the harsh natural conditions and the excessive human disturbances have resulted in barren land, low vegetation productivity and backward social economy in the YB. Therefore, the YB has become a priority area for ecological restoration, in which has implemented multiple and ambitious SWCPs such as GFG, check dams and terraces (Fu et al., 2017). In recent decades, with significant enhancements of socio-economic and ecological conditions, the overall ESs including CSSs in the YB have been significantly improved, which allowed the YB an ideal region to study the interactions between human activities and CSSs (Su et al., 2012).

Therefore, the YB was selected to explore responses of CSSs to multi-SWCPs. The aims of this study were to (a) quantify carbon sequestration and other key ESs in different periods (1990, 2000, 2010 and 2020), (b) explore the direct or indirect influences of multi-SWCPs at sub-catchment scales on carbon sequestration, and (c) provide recommendations for ESs management based on the analysis of spatio-temporal trade-offs.

#### **2 Material and methods**

##### ***2.1 Study site***

Yanhe is a first-order tributary of the Yellow River, draining the 7845 km2 basin in the middle of the LP (108°39′29″–110°28′40″E, 36°22′39″–37°19′12″N). The YB is characterized by a semi-arid climate with an average annual precipitation of ~ 450 mm and temperature of ~9 °C, and grassland is the predominant land-use type (> 50%), followed by farmland and forest (Bai, 2021). The basin is covered by thick and erosion-prone loess, which is the main source of sediment that flows into the Yellow River (Zhang et al., 2021). Therefore, severe soil erosion is common, and over 90% of the territory is composed by gullied and ridges on the Loess plateau area in the YB (Su et al., 2012) (Figure 1). Consequently, a series of SWCPs such as GFG project, check dams and terraces have been implementing on the LP including the YB in nearly half a century (Fu et al., 2017). In the YB, GFG area was almost 2000 km2 based on changes of land-use and vegetation coverage; more than 2000 medium/large size check dams were built to limit runoff and sediment delivery downstream and increase water availability for maize; terraces covered less than 500 km2 due to the high density of the gullies, which are also an effective engineering measure to prevent soil erosion (Figure S1) (URL: <http://www.geodata.cn>).

##### ***2.2 Data Sources***

We attempted to analyze the four services including carbon sequestration, soil conservation, water yield, and crop production in 1990, 2000, 2010, and 2020, respectively. Therefore, Land-use, vegetation, topography, soils, hydrology, climate and human activities including the data of SWCPs need to be collected.

Landsat images (Landsat–5 TM; Landsat–8 OLI) were used for land-use classification and extraction of monthly maximum normalized difference vegetation index (NDVI) based on the platform of Google Earth Engine (GEE) (URL: <https://earthengine.google.com/>). Survey data of above-ground biomass was extracted by literature (Zhang et al., 2011). The 30 m resolution digital elevation model (DEM) and soil erodibility factor map, and the Harmonized World Soil Database (HWSD) for soil types, soil depth and the soil particle composition (URL: <http://www.geodata.cn/>).

Meteorological data mainly include monthly data such as precipitation, high temperature, minimum temperature and total solar radiation, and latitude, longitude and altitude of each station (URL: <https://data.cma.cn/>). Runoff and sediment data were collected from China River Sediment Bulletin (URL: <http://mwr.gov.cn/sj/tjgb/zghlnsgb/>) and Yellow River Conservancy Committee (YRCC). We also used the total crop production data from the County Statistical Yearbook (1989-2021).

The data of SWCPs for check-dams and terraces on the YB, were derived from National Earth System Science Data Center (URL: <http://www.geodata.cn/>). The survey data of check dams, such as dam-construction time, the sedimented storage capacity, and the total storage capacity, were collected from Yan’an City Soil and Water Conservation Bureau. The GFG data, in our study, were extracted by land-use and land cover changes. That is, land-use changes of cultivated land and un-utilized land to forest, grassland and shrub, grassland and shrub to forest, and grassland to shrub. All spatial data were resampled to 30 m pixels.

##### ***2.3 Quantification of ecosystem services***

###### **2.3.1 Carbon sequestration services**

The carbon sequestration services (CSSs) can be represented by the net primary production (NPP) (Lü, 2019). The NPP was utilized to reflect the carbon fixed amount by vegetation and accumulated as biomass (Zheng et al., 2016). Zhu’s model, a process model based on Carnegie-Ames-Stanford Approach (CASA), was used to simulate NPP (Zhu et al., 2007; Potter et al., 1993). The Zhu’s CASA model can be expressed as follows:

(1)

(2)

(3)

Where: *APAR* denotes the vegetation’s absorbed photosynthetic active radiation (MJ·m-2a-1); *ɛ* is the actual light utlize efficiency (g C·MJ-1); *SOL* is the monthly total solar radiation by [spatial interpolation](https://hess.copernicus.org/articles/15/569/2011/); *FPAR* denotes the fraction of *SOL* absorbed by plant canopy, and has a significant linear relationship with NDVI (Ruimy et al., 1994); the constant 0.5 indicates the proportion of effective solar radiation that can be utilized by vegetation; *Tɛ1* and *Tɛ2* are low and high temperature stress coefficients, respectively; *Wɛ* is the water stress coefficients determined by actual/potential evapotranspiration (Zhu et al., 2007), and the evapotranspiration can be estimated by H-S method (Hargreaves & Samani, 1985); *ɛmax* is the maximum light utlize efficiency (g C·MJ-1), here we use 0.389 according to global vegetation month light use efficiency (Potter et al., 1993).

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###### **2.3.2 Water yield services**

Water yield (WY) is the total water resources that flow out of a watershed within a certain period of time, which was simulated by the InVEST model (Liu et al., 2017; Hu et al., 2020). It can be expressed as:

(4)

(5)

Where: W*Y* is the water yield (t·ha-1); *i* indicates the month; *P* is the monthly precipitation; *ET* and *ETo* are the monthly actual evapotranspiration and potential evapotranspiration, respectively (Hargreaves & Samani, 1985). ω denotes the coefficient of water useable by plants, which was calculated by Zhang’s method based on the data of latitude, monthly temperature, soil depth, root depth and the soil particle composition (Zhang et al., 2001; Sharp et al., 2014).

###### **2.3.3 Soil conservation services**

Soil conservation (SC), represents the capacity of ecosystem to control soil and water loss, can mitigate soil erosion directly (Yin et al., 2022). It can be simulated by the difference between potential soil erosion and actual soil erosion (Zhang et al., 2015). The soil conservation was modeled by the China Soil Loss Equation (CSLE) proposed by Liu Baoyuan (2002). Soil conservation *ΔCSLE* (t·ha-1·yr-1) can be expressed as:

(6)

Where: *R* is the rainfall erosivity factor [100 ft·t·in (ac·h·a-1)], and the constant 17.02 is the unit conversion coefficient (Renard et al., 1997); we utilized the monthly and annual rainfall data to estimate *R* ([Quansah, 1981](#Quansah1981)); the soil erodibility factor *K* (t·ha·h·MJ−1·mm−1·ha−1) was extracted by the soil erodibility factor map, and *LS* istopographic factor calculated by Wang’s modified algorithm based on the DEM (Wang et al., [2007](#Wang2007)); *B*, *E* and *T* are the biological, engineering, and tillage measurement factors, respectively. *B* is dominated by the NDVI (Zhang et al., 2021); *T* is directly assigned based on land-use and slope data (Xie et al., 2009); *E* is difficult to quantify due to the uniqueness of engineering measures. Such as check dams, the most important engineering measure in the gully regions of the LP, which were highly effective and played a positive role in services of SC. Sedimentation rates of check dams and gully density of check dam control area were usually ignored for the calculation of *E* (Xie et al., 2009). Thus, a new method was proposed to calculate the *E* factor, as following:

(7)

(8)

Where: *k* is 1.75, a constant coefficient for soil erosion in valley (Ran et al., 2004); *Sc* is the check dam control area; *Sg* is the check-dam control area in valley, and we limit it to no more than 50% of *Sc*. *Sc* and *Sg* were estimated by the special distribution of check dams and DEM based on the hydrological analysis model of ArcMap 10.2; the sedimentation rate *α*, indicating that the sedimented storage capacity (*Vi*) divided by the total storage capacity (*V*), which can be estimated by the siltation ratios for 2347 check dams surveyed in 2009. (Figure S2, Table S1).

###### **2.3.4 Crop production**

Crop production (CP) correlated significantly with NDVI (Mkhabela et al., 2011). We need to decompose the statistics of county-level crop production to a pixel scale of 30 m × 30 m according to the distribution of NDVI, and the area of towns was also considered, as follows:

(9)

(10)

(11)

(12)

Where: *Cc*, *Ct* and *Cx* are crop production under county, town and pixel scale, respectively. *β* represents the proportion of crop production in town *i* of a county, and estimated by the mean NDVI (*NDVImean*) and thearea of the town *Si*; γ is the proportion of crop production in pixel of a town, which is calculated by the NDVI of pixel *x* (*NDVIx*).

###### **2.3.5 Accuracy assessment**

Linear regression was utilized to test the robustness and the ability of models to simulate ecosystem services. The performance of the models was assessed using the fitting indicator of *R*2 and the significant level (*P*). Simulations are reliable when *R*2 > 0.5 and *P* < 0.05 (Diamond, 1990).

##### ***2.4 Statistical analysis***

###### **2.4.1** **Structural Equation Modeling (SEM)**

The structural equation model (SEM) was established to estimate impacts of check dams, terraces and GFG on ecosystem services, and the interaction mechanism between ecosystem services. The package of PiecewiseSEM in R studio software was used to set up the SEM model ([Jonathan](https://besjournals.onlinelibrary.wiley.com/action/doSearch?ContribAuthorRaw=Lefcheck%2C+Jonathan+S), 2016). The linear mixed effects models were utlized to fit SEM paths between SWCPs, ecosystem services and carbon sequestration, specifying in each case period as a random effect. The direct and indirect effects of SWCPs to ESs, especially for the CSSs (NPP) have been hypothesised (Figure 2). We removed the no significant link between SC and CP to simplify the model (Fisher's C = 2.468 with P-value = 0.291 and on 2 degrees of freedom).

###### **2.4.2 Statistical distributions of ecosystem service estimates**

The YB was divided into 243 sub-basins based on the hydrological analysis model of ArcMap 10.2 software, and the average of ESs was extracted to them. Hot spots analysis was used to identify high-value cluster sub-basins (hot spots) and low-value cluster sub-basins (cold spots) for different ecosystem services based on the software of ArcGIS 10.2, and the clustering degree was determined by the critical value Z-scoreand the significance level P-value (<https://desktop.arcgis.com/zh-cn/arcmap/latest/tools/spatial-statistics-toolbox/what-is-a-z-score-what-is-a-p-value.htm>). Then, the spatial-temporal associations among two ecosystem services can be simulated by spatial overlay analysis based on hot spots analysis.

#### **3 Results**

##### ***3.1 Spatio-temporal distribution of ecosystem services***

ESs of NPP, WY, SC and CP in the YB were increased to varying degrees from 1990 to 2020, although lower in 2000. NPP saw a significant spatial heterogeneity because of different vegetation types from northwest to southeast. It was increased greatly from 228 t·ha-1·yr-1 initially to 457 t·ha-1·yr-1 in 2020. WY decreasing and increasing before and after 2000, respectively. The pattern of WY was similar to that of precipitation decreasing gradually from south to north, and was differentiated in different land-use types under a smaller scale. SC was evenly distributed in the whole YB, which has been increased to 1365 t·ha-1·yr-1 with 4 times more compared to 333 t·ha-1·yr-1 in 1990. The annual average of CP was 89 kg·ha-1·yr-1 with a slight increase trend. However, the regional imbalance of CP was highlighted in recent decades (Figure 3 a1–e4).

The four simulated ESs of NPP, WY, SC and CP were reliable compared to observed data (*R*2 > 0.5 and *P* < 0.05). That is, the modeled NPP was lower, approaching half of above-ground biomass, which was affected by the selection of sample sites with higher vegetation coverage of the vegetation community. The simulated WY was much higher than observed data of runoff, because the observed data did not include water resources other than runoff (Figure 3 f1–f4).

##### ***3.2 Impacts of SWCPs and ESs on NPP***

The SEM indicated that GFG and check dams were positively to NPP with total effects of 0.80 and 0.16, respectively, while terraces were negatively to NPP with total effects of -0.72 (Figure 4a). In addition, WY was negatively to NPP with total effects of -0.77, while SC and CP were positively to NPP with total effects of 0.76 and 0.22, respectively (Figure 4b). 57% of NPP in the YB was explained by ESs and SWCPs. That is, GFG improved NPP ultimately and directly, SC increased NPP indirectly by check dams increasing. Although, effects of terraces to CP were positive, it can be ignored due to the lower explanation (<10%). On the contrary, the negative effects of terraces to SC decreased NPP to a large extent (Figure 4c).

##### ***3.3 Trade-offs and synergies* *between NPP and other ESs***

By using the SEM approach, we found that trade-offs occurred between NPP and SC or CP, while synergies occurred between NPP and WY (Figure 4). Additionally, there was significant spatial-temporal heterogeneity in trade-offs and synergies between NPP and other ESs, although more than 70% of the basin was no significant associations. The spatial distribution of associations between NPP and WY was similar to that between NPP and SC from 1990 to 2020. That is, synergies in the upper reaches of the YB, while trade-offs in other parts of the basin, which were opposite to the relationships between NPP and CP. Moreover, the trade-offs between NPP and WY were increasing, while the synergies between NPP and SC, and between NPP and CP were decreasing. Overall, synergies were decreasing and trade-offs were increasing, that would be a challenge for ecosystem management in future (Figure 5).

#### **4 Discussion**

##### ***4.1*** ***GFG was the most important factor to improve carbon sequestration services***

GFG is the most important and effective factor to increase NPP directly (Figure 4). Before 2000, the undue activities (i.e. indiscriminate logging, overgrazing and overexploitation of groundwater) under harsh natural conditions has led to more serious soil erosion, forest reduction, grassland degradation, water shortage and other problems (Kochtcheeva & Singh, 2000; Su et al., 2012). Therefore, GFG, the largest active revegetation programme implemented from 1999, which has doubled the vegetation cover of the LP in a decade or so (Chen et al., 2015). Thus, CSSs have undoubtedly and greatly improved at the same time (Su et al., 2012). Check dams, the most common SWCPs, improved CSSs indirectly by the increasing SC (Figure 4). There are more than 100 thousand check dams widely distributed in the LP, especially the gully region of the LP (Wang et al., 2011). The carbon storage of check dams on the LP accounts for about 20% of the total forest carbon storage in China (Wang et al., 2011; Zhao & Zhou, 2006). Moreover, there was a higher amount of carbon sequestration on slope systems by check dams and terraces compared to the direct carbon sequestration through vegetation restoration (Lu & Ran, 2015). Terracing is also an important project of agricultural production and soil and water conservation on the LP (Qi et al., 2020). However, we found that terraces account for up to 70% of the farmland, which makes the SC service of terraces much lower than the CP service, and decreased CSSs indirectly (Figure 4). Therefore, terracing was significantly positively correlated with CP, while negatively correlated with SC. That is, terraces supported CSSs, but it had weak support for vegetation carbon sequestration as a non-predominant land use type (Zhang et al., 2020). Overall, GFG was the most important SWCP to improve carbon sequestration services.

##### ***4.2 Check dams can balance trade-offs between CSSs and other ESs***

It is pleasing to note that the ESs have all improved to varying degrees (Figure 3). However, this consistent increase is likely to be short-lived or unsustainable due to increasing trade-offs and decreasing synergies between NPP and other services (Figure 5). It is especially important for decision maker to minimize tradeoffs and amplify synergies among ESs (Zhao et al., 2021). Here, by understanding the spatial-temporal associations among ecosystem services and their driving factors, we can increase the probability of lower trade-offs and higher synergy between ESs and increase CSSs at the same time (Zhang et al., 2020). For example, GFG appears to be the best program to increase NPP, but continued expansion of GFG increases trade-offs among ESs, especially regions where water resources are relatively scarce (Figure 4) (Wang et al., 2007; He et al., 2020; Hu et al., 2021). Moreover, large-scale afforestation has aggravated soil water scarcity and even formed dry soil layers in the deep soil layers, which resulted trees with a low survival rate and “small aged trees” (Yan et al., 2015). Check dams, effective engineering measures for soil and water conservation, have the potential to replenish dry soil layers caused by GFG, although have reduced runoff in some degree (Jin et al., 2012; Peng et al., 2019; Yuan et al., 2022). What's more, studies have shown that check dams can increase the regular flow of water in ditches and promote regional water yield (Liang & Cheng, 2003). Therefore, check dams can balance trade-offs between NPP and other ESs due to the large-scale GFG. In addition, terraces are also important SWCPs in China (Xu et al., 2011; Liu et al., 2021). However, terracing was high negative to NPP due to its main function of farming in our study (Figure 4). Therefore, increasing the proportion of non-agricultural terraces (i.e. reverse-slope terraces, level benches and fish-scale pits) may be another effective way to balance trade-offs and increase CSSs (Qi et al., 2020).

##### ***4.3 Implications***

It has been found that GFG was the most important project to enhance CSSs, followed by check dams, terraces were encouraged under certain conditions at watershed scale. However, under the sub-watershed scale, the spatio-temporal heterogeneity of trade-off or synergistic relationships between different ESs leads to spatial variation in the layout and the intensity of SWCPs. In other words, policy makers usually need to balance the trade-offs among ESs in different spatio-temporal scales (Su et al., 2012). In the upper reaches of the basin, where synergistic relationships dominate except the trade-off between NPP and CP due to the mismatch between low NPP and high CP, suggesting that any enhancement of services other than CP contributes to the increase in NPP. The opposite is true in the lower and middle reaches. However, the increasing trade-offs and decreasing synergies between NPP and other services indicate that we should not massively increase SWCPs, but rather consolidate what we already have. Therefore, we advocate (1) GFG with a focus on vegetation conservation rather than revegetation; (2) encouraging the construction of a large number of small check dams to slow runoff rather than reduce it (Liang & Cheng, 2003); (3) the functional conversion of ESs in terraces from CP to SC, and (4) further expansion of afforestation in the southern part of the basin with a relatively humid climate and higher WY.

#### **5 Conclusions**

Over the past 30 years, large-scale and multiple soil and water conservation projects dramatically improved carbon sequestration services in the Yanhe Basin. GFG had a positive effect on carbon sequestration, which was five times higher than check dams, while terraces had a negative effect on carbon sequestration due to the high proportion of farmland (70%). However, the increasing trade-offs and decreasing synergies indicate that we need to change the previous strategy on vegetation restoration. That is, priority for GFG but focus on vegetation protection; construction of small check dams to slow runoff; transformation of terraces from agricultural to non-agricultural functions; and further expansion of afforestation on the southern edge of the basin with good hydrological conditions. Such recommendations may decrease trade-offs and enhance synergies while increasing carbon sequestration, which may facilitate the restoration of degraded ecosystems and the sustainable use of ecosystem services, and benefit carbon neutrality targets in China.

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#### **Data availability statement**

Data availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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#### **Figures:**



Figure 1 General description of the Yanhe Basin (YB). (a) represents location of the YB and general description of the river systems; (b) and (c) represent the annual precipitation and NDVI in the YB from 1982 to 2015, respectively; (d) represent the landforms of the loess hill and gully region covered by terraces and vegetation.



Figure 2 Hypothesised direct and indirect links between soil and water conservation measures (i.e. check dams, terraces and the Grain for Green project), ecosystem services (i.e. water yield, soil conservation and crop product) and carbon sequestration (i.e. NPP).



Figure 3 Simulations and validations of ecosystem services in the Yanhe Basin from 1990 to 2020. NPP, WY, SC and CP represent ecosystem services of carbon sequestration, water yield, soil conservation and crop production, respectively; a1–a4, b1–b4, c1–c4 and d1–d4 are simulated ecosystem services of NPP, WY, SC and CP in different periods, respectively; e1-e 4 represent the univariate linear regression slopes, which are the increases in different ESs per 10 years; and f 1–f4 are cross-validations between observed and estimated values of NPP, WY, SC and CP, respectively.



Figure 4 Path diagram showing how ecosystem services (ESs) and soil and water conservation projects (SWCPs) affect NPP directly and indirectly.



Figure 5 Trade-offs and synergies between NPP and other ecosystem services (i.e. WY, SC and CP) in the Yanhe Basin from 1990 to 2020; NPP, WY, SC and CP represent ecosystem services of carbon sequestration, water yield, soil conservation and crop production, respectively; a1–a4, b1–b4 and c1–c4 are relationships between NPP & WY, NPP & SC and NPP & CP in different periods, respectively