How ecological restoration alters ecosystem services: an analysis of carbon sequestration in China's Loess Plateau

Xiaoming Feng[1], Bojie Fu[1], Nan Lu[1], Yuan Zeng[2] & Bingfang Wu[2]

[1]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China, [2]Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China.

Restoring disturbed and over-exploited ecosystems is important to mitigate human pressures on natural ecosystems. China has launched an ambitious national ecosystem restoration program called Grain to Green Program (GTGP) over the last decade. By using remote sensing techniques and ecosystem modelling, we quantitatively evaluated the changes in ecosystem carbon sequestration since China's GTGP program during period of 2000–2008. It was found the NPP and NEP in this region had steadily increased after the initiative of the GTGP program, and a total of 96.1 Tg of additional carbon had been sequestered during that period. Changes in soil carbon storage were lagged behind and thus insignificant over the period, but was expected to follow in the coming decades. As a result, the Loess Plateau ecosystem had shifted from a net carbon source in 2000 to a net carbon sink in 2008. The carbon sequestration efficiency was constrained by precipitation, and appropriate choices of restoration types (trees, shrubs, and grasses) in accordance to local climate are critical for achieving the best benefit/cost efficiency.

Ecological restoration, which aims to restore disturbed ecosystems, has been an important approach to mitigate human pressures on natural ecosystems[1] and to improve ecosystem services[2]. China's Grain to Green Program (GTGP) is such a national ecological restoration program. Started in 1999, GTGP is the largest ecological restoration program in the developing world, with an ambitious goal to rehab China's degraded and disturbed ecosystems. The Chinese government has committed a spending over $US 40 billion on the GTGP program by 2050[3], and over the past decade approximately $US 28.8 billion has already been invested on the conversion of cultivated land on steep slopes ($\geq 25°$) to perennial vegetation.

Since its implementation in 1999, the GTGP program has made remarkable contribution to China's vegetation recovery. Both ground based inventory data and satellite based Normalized Different Vegetation Index (NDVI) data has revealed a significant increase in the area of natural and semi-natural vegetation over the regions covered by the GTGP program[4,5]. For instance, inventory data show that the GTGP program has helped re-establish semi-natural vegetation on 14.7 million hectares of previously cultivated slopes and 17.3 million hectares on abandoned agricultural lands[4]. This continuous increase in vegetation cover is expected to change ecosystem services, including the potential in sequestrating greenhouse gases, which has not yet been quantitatively evaluated. Furthermore, the effectiveness of ecological restoration as well as its carbon sequestration consequence can be highly variable across climatic gradients[6]. For example, vegetation in humid southern China now accounts for more than 65% of national carbon sequestration since the implementation of national ecosystem restoration[7], while the effectiveness of vegetation restoration is limited in arid regions[8]. Therefore, it is also important to examine the spatial and regional variances in the ecosystem services from large-scale restoration program. Such information is particularly important for adjusting current and planning for future restoration program in a more benefit/cost efficient way.

In this paper, we investigated the ecosystem carbon sequestration in the Loess Plateau, a prioritized pilot region covered by the ongoing GTGP program (Fig. 1), over the period of 2000–2008. Home to 108 million people, the Loess Plateau in Northern China is one of the world's most eroded regions, as a result of thousands of years of over-exploitation over its fragile ecosystems built on dry powdery wind-blown soil[9]. Effectively restoring the
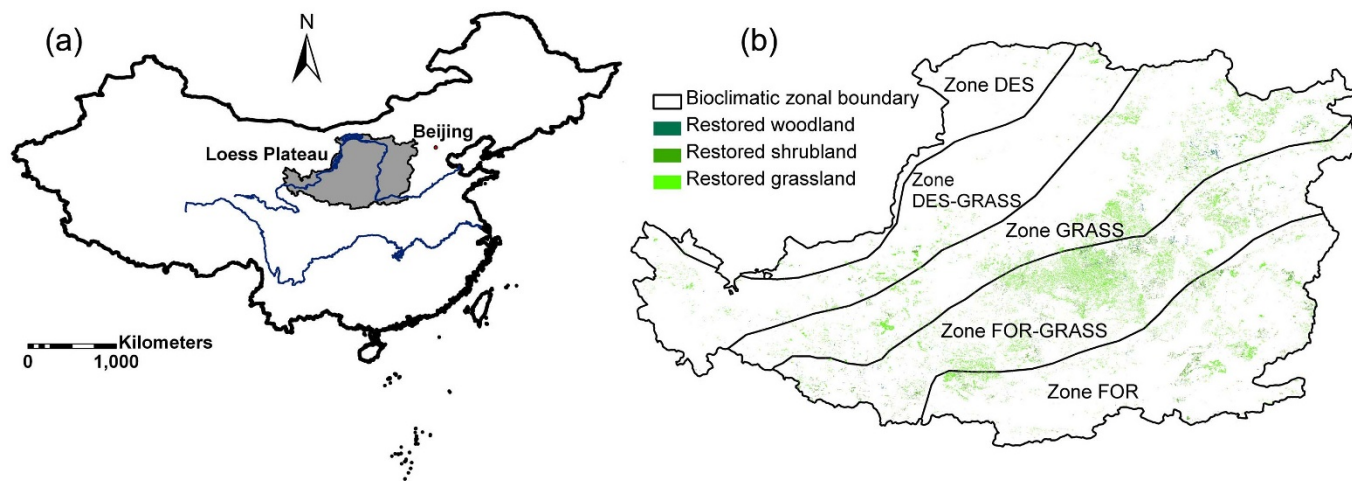
Figure 1 | (a) Location of the Loess Plateau and (b) distribution of different restoration types among the bioclimatic zones: Zone FOR (semi-humid forests), Zone FOR-GRASS (semi-humid to semi-arid forest-grasslands), Zone GRASS (semi-arid typical grasslands), Zone DES-GRASS (arid and semi-arid desert-grasslands) and Zone DES (arid deserts). Map created in ArcMap 9.3 (Environmental Systems Resource Institute, ArcMap 9.3 ESRI, Redlands, California).

semi-natural and natural vegetation through the GTGP program in this over-exploited fragile ecosystem is therefore a critical measure for the welfare of the people inhabited in this plateau and beyond[10]. Thus, our aim in this paper is to quantitatively evaluate the efficiency of the GTGP program in improving carbon sequestration in water limited arid Loess Plateau. By incorporating satellite derived NDVI data, climate data, and ecosystem modeling, we investigated the change in ecosystem net primary productivity (NPP), soil carbon storage and net ecosystem productivity (NEP) over the Loess Plateau since the implementation of the GTGP program. Finally,

we also discussed how the amount of precipitation may affect the GTGP efficiency in carbon sequestration.

Results

Annual NPP increased over the Loess Plateau since the implementation of the GTGP program. We first examined the change in annual NPP over the Loess Plateau, which showed an increasing trend during the period 2000–2008. The total annual NPP increased from 0.170 Pg C in 2000 to 0.217 Pg C in 2008: a significant rate of 9.4 g C m^{-2} per year (P < 0.01). This increasing trend in
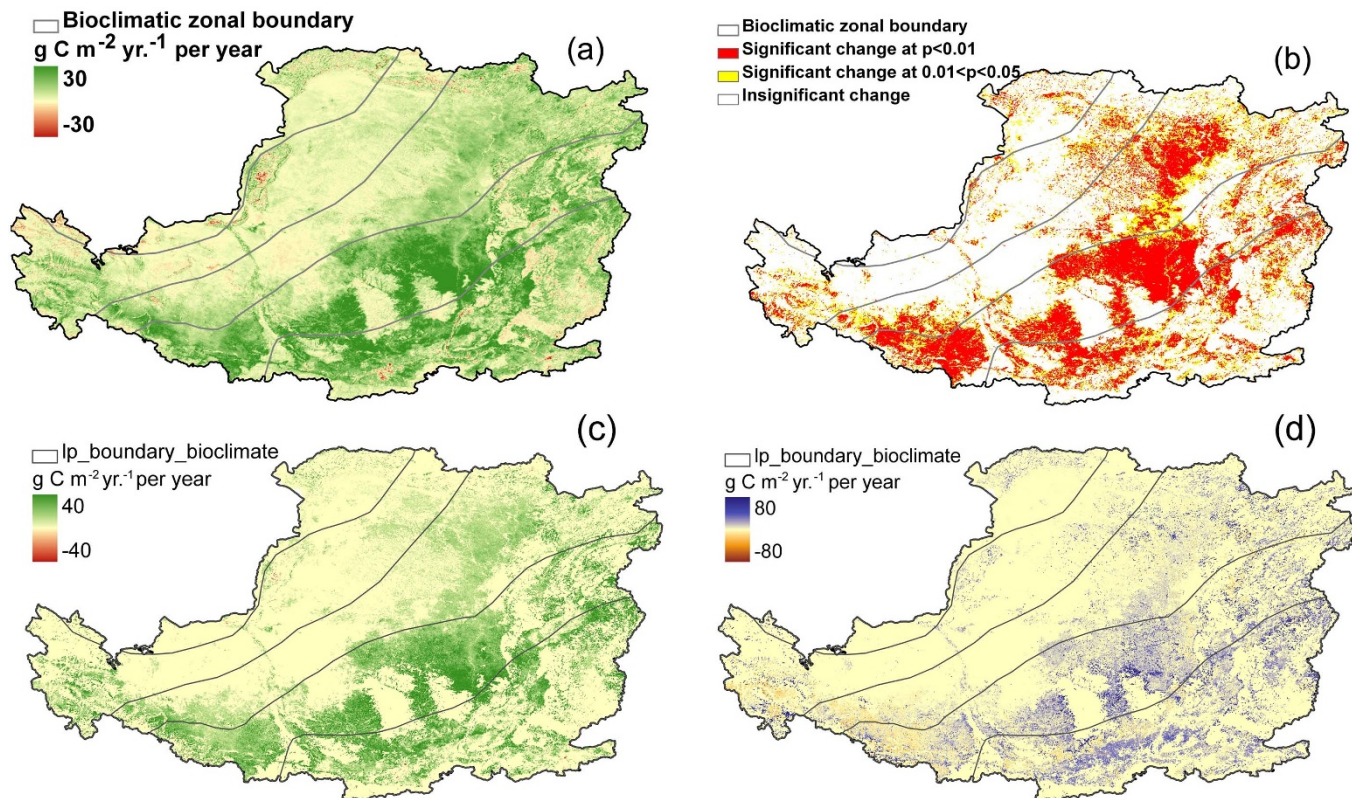

Figure 2 | Distribution of (a) the increment of annual NPP and (b) the significant level of the increment of annual NPP on the Loess Plateau during 2000–2008. Distribution of the increment of (c) annual NEP and (d) soil carbon storage following the GFGP program on the Loess Plateau during 2000–2008. Map created in ArcMap 9.3 (Environmental Systems Resource Institute, ArcMap 9.3 ESRI, Redlands, California).

annual NPP is also significant (P < 0.05) in 37% of the Loess Plateau area, where the mean rate of annual NPP accumulation was 17.1 g C m^{-2} per year (Fig. 2a).

The plateau can be divided into five bioclimatic zones: semi-humid forests (FOR), semi-humid to semi-arid forest-grasslands (FOR-GRASS), semi-arid typical grasslands (GRASS), arid and semi-arid desert-grasslands (DES-GRASS) and arid deserts (DES), descending by the amount of annual precipitation received[11] (Fig. 1, Supplementary Table S1). The increasing trend in annual NPP during 2000–2008 is also found for each of the five bioclimatic zones, with varied magnitudes. The largest increasing trend was found in Zone FOR-GRASS (15.3 g C m^{-2} per year, P < 0.01), followed by Zone FOR (12.4 g C m^{-2} per year, P < 0.01), Zone GRASS (7.4 g C m^{-2} per year, P < 0.01) and Zone DES-GRASS (3.8 g C m^{-2} per year, P < 0.05). The change is less obvious in Zone DES (2.5 g C m^{-2} per year, P = 0.08) (Fig. 2a, Fig. 2b).

Increased annual NEP over the Loess Plateau during 2000–2008. NEP of the Loess Plateau also significantly increased from a carbon source of −0.011 Pg C in 2000 to a carbon sink of 0.108 Pg C in 2008, equaling to a rate of 19.2 g C m^{-2} per year (P < 0.01). While all of them except Zone FOR were net carbon sources in the year 2000, by 2008, all five zones functioned as net carbon sinks with annual NEP being 0.040 Pg C (37.1% of the total annual NEP), 0.035 Pg C (31.9%), 0.016 Pg C (14.6%), 0.014 Pg C (12.4%) and 0.004 Pg C (4.1%), respectively (Fig. 2c).

The significantly increasing NEP trend was also found for each bioclimatic zone during 2000–2008, with variable magnitudes. Zone FOR-GRASS had the highest trend of annual NEP increase (26.7 g C m^{-2} per year, P < 0.01), followed by Zone FOR (24.8 g C m^{-2} per year, P = 0.01), Zone DES-GRASS (17.1 g C m^{-2} per year, P < 0.01), Zone GRASS (11.5 g C m^{-2} per year, P < 0.01), and Zone DES (9.9 g C m^{-2} per year, P < 0.01) (Fig. 2c).

Increased soil carbon storage over the Loess Plateau during 2000–2008. Soil carbon storage for the Loess Plateau increased from 2.639 Pg C in 2000 to 2.682 Pg C in 2008, a rate of 8.5 g C m^{-2} per year. The increasing trend was also found for each bioclimatic zone with variable magnitudes. Zone FOR had the highest trend (13.9 g C m^{-2} per year), followed by Zone FOR-GRASS (9.7 g C m^{-2} per year), zone DES-GRASS (6.3 g C m^{-2} per year), Zone GRASS (4.8 g C m^{-2} per year) and Zone DES (3.2 g C m^{-2} per year) (Fig. 2d). Yet all the trends were statistically insignificant (P > 0.05), probably due to the short time duration since the implementation of the GTGP program.

Ecosystem restoration and carbon sequestration. Apart from the implemented GTGP program, changes in climate may also have contributed to the past decade's significant ecosystem carbon sequestration in the Loess Plateau. Thus we also examined the changes in annual precipitation (P) and mean annual temperature (MAT) over 2000–2008. However, we found no significant change in P or MAT for either the entire region or any of the separate bioclimatic zones (Fig. 3). Statistical analyses also showed no significant correlations between NPP or NEP and the climate variables (P > 0.45). Hence the observed significant increases in NPP and NEP over the Loess Plateau were unlikely caused by climate change. On the other hand, the places experiencing a significant increase in annual NPP were found mostly within the GTGP program areas (comparing Fig. 1b and Fig. 2b). In addition, the rates of annual NPP and NEP increase for each zone were linearly correlated with the acreage of restored shrubland in that zone (R^2 ≥ 0.78, P ≤ 0.04) (Fig. 4). These results suggest that the increased annual NPP and net ecosystem sequestration across the Loess Plateau from 2000–2008 were mostly due to the implemented ecological restoration program.

While changes in climate may not be responsible for the significantly increased NPP in the Loess Plateau, the carbon sequestration
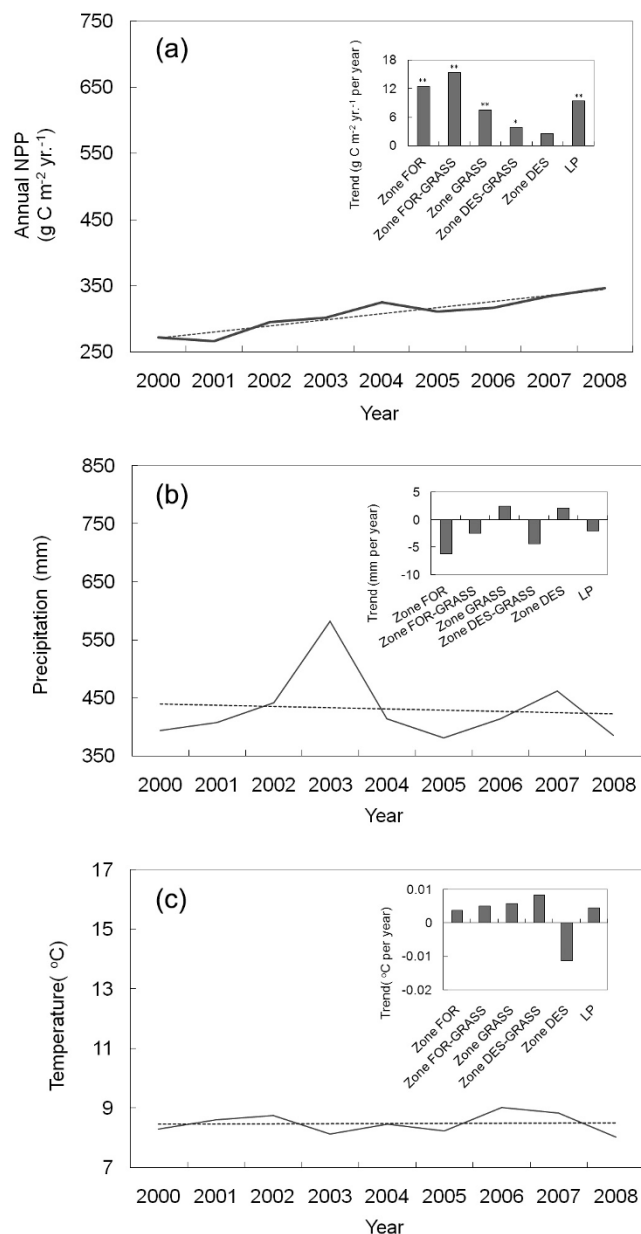

Figure 3 | Time series of (a) annual NPP, (b) annual precipitation and (c) temperature during 2000–2008 across the Loess Plateau. The dotted lines are linear regression fits for each set of data: y = 9.4x − 18232.0 (R^2 = 0.88, P = 0.0001) for annual NPP, y = −2.1x + 441.3 (R^2 = 0.01, P = 0.81) for annual precipitation and y = 0.004x + 8.5 (R^2 = 0.00, P = 0.93) for temperature. The inset of each diagram shows trends for each bioclimatic zone. ** means a significant trend at P < 0.01, and * means a significant trend at P < 0.05.

efficiency of the GTGP program was still limited by precipitation. Precipitation can have a direct effect on plant characteristics such as size, plant structure as well as plant density of the restored vegetation[12,13]. For Zone FOR, the woodland restoration type had the highest amounts of NPP and NEP. For Zone FOR-GRASS, restored shrubland had the highest amounts of NPP and NEP; and for Zone GRASS, shrubland restoration resulted in the highest amount of NPP, and woodland restoration had the highest NEP. For Zone DES, restored grassland performed best in terms of the amount of NPP or NEP (Table 1). The results suggest the appropriate restoration types in accordance to local climate should be considered for achieving the best efficiency.
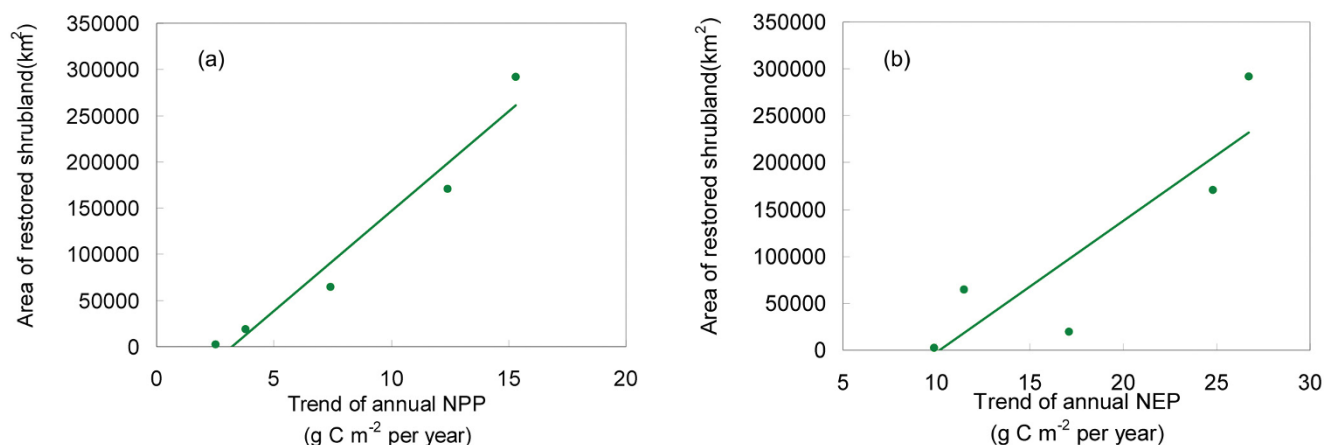
Figure 4 | Linear correlation (a) between annual NPP and zonal acreage for restored shrubland: y = 21540x − 68463(R² = 0.95, P = 0.004); and (b) between annual NEP and zonal acreage for restored shrubland: y = 14053x − 142997 (R² = 0.78, P = 0.04).

Discussion

Our results demonstrated a significantly increasing trend in ecosystem carbon sequestration over the fragile Loess Plateau (19.2 $g\,C\,m^{-2}$ per year on average) since the implementation of the GTGP program, which resulted in a total of 96.1 Tg C fixed in this land. The Loess Plateau ecosystem had shifted from a net carbon source in 2000 to a net carbon sink in 2008. This sequestration of carbon is equivalent to 6.4% of China's total fossil fuel carbon dioxide emissions in 2006[14]. It should be noted that the restored area in the Loess Plateau accounted for about 6.4% of the total area covered by the GTGP program[15]. Therefore, the GTGP program has made substantial contribution in mitigating China's anthropogenic CO_2 emission.

Our analysis showed that the current increase of NEP was mainly contributed by enhanced NPP, and the trend of soil carbon storage in the first nine years of the GFGP program was found insignificant. This might be because changes in soil carbon storage usually lag behind that of aboveground productivity[16,17]. The time of source-to-sink transition was 3–8 years and SOC recovery was 10–15 years. In a recent study[18], China's forest soil in 2000–2007 was estimated a carbon sink as large as 28 $Tg\,C\,yr^{-1}$. However, this large soil carbon sink may be overestimated by assuming a constant ratio of biomass/soil carbon storage. Nonetheless, with the progress of the ecological restoration program, enhanced soil carbon storage is expected to follow in the coming decades because of improved carbon inputs and increased soil carbon storage capacity.

The increment of annual NPP and NEP was highest in Zone FOR-GRASS, where mean annual precipitation is about 450–550 mm. This is the result of both the largest proportion of restored land and the full phenological development of restored trees in the FOR-GRASS region. Where precipitation is less than 500 mm, the planted trees were found in reduced stature and shrub-like in appearance[19]. Our work also demonstrated the rates of different restoration types in increasing annual NPP for different bioclimatic zones. In terms of carbon sequestration potential, our results showed there is not a universally best restoration type for all climate types. The vegetation restoration in the Loess Plateau is especially limited by the availability of water[19]. Climate modeling predicts a drier and warmer climate to be expected for the coming decades in the Loess Plateau, which will cause greater deficits of water availability in this already water-limited region. Given the high cost of human aided ecological restoration, it is therefore particularly important to carefully choose the appropriate restoration vegetation type according to the local climatic restraints especially precipitation to achieve best ecosystem services.

Methods

Study region. Located in northern China, the Loess Plateau covers an area of approximately 640,000 km². Annual precipitation in this region varies from 200 to 800 mm, and the annual mean air temperature is 7°C. Except for the most humid southeastern part which is dominated by forests, over 80% of the Loess Plateau is covered by arid and semi-arid grassland ecosystems (see Supplementary Fig. S1 online). As the core region where Chinese culture was born and cultivated, the Loess Plateau had a long history of agricultural exploitation. Since the implementation of GTGP program in 1999, grasses (species like *Medicago sativa*), shrubs (e.g., *Caragana microphyllla, Hippophae rhamnoides*) and trees (e.g., like *Robinia pseudoacacia, Pinus tabulaeformis, Ziziphus jujube* and *Malus pumila*) have been planted on land formerly cultivated for crops[11]. Cultivated cropland decreased by 10.8% since the implementation of the GTGP from 2000–2008. Woodland increased by 4.9%, while shrubland and grassland increased by 6.6%[10].

Estimating NPP from remotely sensed data. We used the terrestrial Carnegie-Ames-Stanford Approach (CASA) ecosystem model to estimate ecosystem net primary production (NPP) from satellite data. The CASA NPP is calculated as the product of the modulated 'Absorbed Photosynthetically Active Radiation' (APAR) and the light use efficiency (LUE) factor[20]:

$$NPP(x,t) = APAR(x,t)\varepsilon(x,t)$$

Where NPP(x,t) represents carbon sequestration in spatial location x and time t (g $C\,m^{-2}$), APAR(x,t) is the canopy-absorbed incident solar radiation (MJ m^{-2}), and $\varepsilon(x,t)$ is the light use efficiency (g $C\,MJ^{-1}$) of APAR. Most of the inputs needed to run

Table 1 | Annual NPP and NEP of the resotred ecosystems and their trends since the implementation of the GFGP program. ** means a significant trend at P < 0.01, and * means a significant trend at P < 0.05

	Annual NPP (g C m⁻²) and the trend (g C m⁻² per year)			Annual NEP (g C m⁻²) and the trend (g C m⁻² per year)		
	Restored woodland	Restored shrubland	Restored grassland	Restored woodland	Restored shrubland	Restored grassland
FOR	652.2 (5.1*)	550.5 (16.5**)	563.7 (17.5**)	304.4 (21.0*)	289.9 (22.2**)	277.2 (24.8*)
FOR-GRASS	402.6 (21.4**)	439.4 (19.3**)	429.8 (23.1**)	233.4 (25.1**)	263.7 (23.9**)	235.1 (27.2**)
GRASS	257.2 (10.1*)	264.0 (11.0**)	228.7 (9.9**)	118.2 (13.6**)	92.8 (10.0*)	106.5 (11.6**)
DES-GRASS	290.6 (4.8)	202.9 (3.0)	193.6 (3.5)	148.8 (13.2**)	89.8 (11.7**)	102.2 (12.3**)
DES	127.2 (2.9)	181.1 (−1.5)	213.4 (3.2)	113.3 (6.6)	108.3 (7.9**)	149.6 (7.3**)
Loess Plateau	344.2 (14.5**)	406.0 (13.8**)	372.0 (16.9**)	195.6 (18.6**)	256.6 (21.6**)	191.8 (20.8**)

the CASA model can be derived from remote sensing data[21]. Compared to other process-based models, the CASA model has been proven of the most efficient approach in simulating carbon cycles in the Loess Plateau[20] (Supplementary Table S2).

Data inputs for the CASA model include land cover, NDVI, and climate data. Land covers for the Loess Plateau in 2000 and 2008 were extracted from Landsat TM/ETM. We used the 1-km MODIS NDVI data, which were composites of 16-day NDVI maximum values and acquired from the MODIS Land Processes Distributed Archive Center (http://wist.echo.nasa.gov/api). In addition, daily meteorological data (solar radiation, temperature and precipitation) for the period 2000–2008 were obtained from 172 stations within and near the Loess Plateau, and were interpolated to a 1-km resolution on a 1-km resolution digital elevation model layer with the thin-plate smoothing spline method using ANUSPLIN 3.1. Carbon sequestration rates were calculated on a monthly basis.

Soil carbon storage and annual NEP. We used the CENTURY model[22] to estimate soil carbon storage in the upper 50 cm soils and annual NEP, the latter is the difference between NPP and ecosystem microbial respiration. CENTURY is composed of a plant production submodel, soil organic matter submodel and water budget model. The model runs with a monthly time step. In this study, CENTURY model was first run for 50 years under the land use before the GTGP program to get the initial soil carbon levels of the Loess Plateau. During the period of 1999–2000, remotely sensed NPP was used as the monthly production to drive the model simulation. Plant and soil variables in CENTURY model were mainly acquired from the Chinese ecosystem research network (CERN) (http://www.cerndata.ac.cn/) For unavailable parameter values such as extreme temperatures of plant growth, structural death, decomposition rate, and cultivation/harvest factors, archived sample values from the CENTURY parameter database were referred to (http://www.nrel.colostate.edu/projects/century/).

Data analysis. We used linear regression to estimate the trends of annual carbon sequestration during 2000–2008 for each 1×1 km^2 grids, as well as for each of the five bioclimatic zones and the entire region.

The acreage of cultivated land restored to semi-natural habitats in each bioclimatic zone was used as a proxy for the extent of implementation of the GTGP. We identified the effect of GTGP first by analysing the carbon sequestration trend for each restored ecosystem type (grassland, shrubland and woodland), then by comparing the acreage of restored land with zonal annual carbon sequestratoion increase. Finally, we identified the effect of local precipitation on carbon uptake by comparing zonal carbon sequestration with precipitation gradients.

1. Holl, K. D., Crone, E. E. & Schultz, C. B. Landscape restoration: Moving from generalities to methodologies. *BioScience* **53**, 491–502 (2003).
2. Doren, R. F., Trexler, J. C., Gottlieb, A. D. & Harwell, M. C. Ecological indicators for system-wide assessment of the greater everglades ecosystem restoration program. *Ecol. Indic.* **9**, 2–16 (2009).
3. Xu, Z., Bennett, M. T., Tao, R. & Xu, J. China's sloping land conversion programme four year on: current situation and pending issues. *Int. For. Rev.* **6**, 317–326 (2004).
4. Chen, X., Zhang, X., Zhang, Y. & Wan, C. Carbon sequestration potential of the stands under the Grain for Green Program in Yunnan Province, China. *Forest Ecol. Man.* **258**, 199–206 (2009).
5. Xin, Z., Xu, J. & Zheng, W. Spatiotemporal variations of vegetation cover on the Chinese Loess Plateau (1981–2006): Impacts of climate changes and human activities. *Sci. China Ser. D* **51**, 67–78 (2008).
6. McDowell, N. G. *et al.* The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends Ecol. Evol.* **26**, 523–532 (2011).
7. Piao, S. *et al.* The carbon balance of terrestrial ecosystems in China. *Nature* **458**, 1009–1014 (2009).
8. Cao, S. *et al.* Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration. *Earth-Sci Rev.* **104**, 240–245 (2011).
9. Wang, Y. & Shao, M. Spatial variability of soil physical properties in a region of the Loess Plateau of PR China subject to wind and water erosion. *Land Degrad. Dev.* **24**, 296–304 (2013).
10. Lü, Y. *et al.* A policy-driven large scale ecological restoration: Quantifying ecosystem services changes in the Loess Plateau of China. *PLoS ONE* **7**, e31782 (2012).
11. Zhang, H. & Huang, Z. Bio-climatic division and restoration of the degraded ecosystem on the Loess Plateau. *J. Arid Land Res. Environ.* **15**, 64–71 (2001).
12. Engelbrecht, B. M. J. *et al.* Drought sensitivity shapes species distribution patterns in tropical forests. *Nature* **447**, 80–82 (2007).
13. Krishnan, P. *et al.* Impact of changing soil moisture distribution on net ecosystem productivity of a boreal aspen forest during and following drought. *Agr. Forest Meteorol.* **139**, 208–223 (2006).
14. Gregg, J. S., Andres, R. J. & Marland, G. China: emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production. *Geophys. Res. Lett.* **35**, L08806 (2008).
15. Zhang, K. *et al.* Change in soil organic carbon following the 'Grain for Green' programme in China. *Land Degrad. Dev.* **21**, 13–23 (2010).
16. Poeplau, C. *et al.* Temporal dynamics of soil organic carbon after land-use change in the temperate zone- carbon response functions as a model approach. *Global Change Bio.* **17**, 2415–2427 (2011).
17. Li, D., Niu, S. & Luo, Y. Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta-analysis. *New Phytol.* **195**, 172–81 (2012).
18. Pan, Y. *et al.* A large and persistent carbon sink in the world's forests. *Science* **333**, 988–993 (2011).
19. Hou, Q., Huang, X., Han, S. & Zhang, X. Study on the forming of "small olded tree and transforming way in the Loess Plateau I. the distribution and growth nature of the small olded tree. *J. Soil Water Conser.* **5**, 64–72 (1991).
20. Potter, C. S. *et al.* Terrestrial ecosystem production: a process model based on global satellite and surface data. *Global Biogeochem. Cy.* **7**, 811–841 (1993).
21. Xing, X. *et al.* Simulating net primary production of grasslands in northeastern Asia using MODIS data from 2000 to 2005. *J. Geogr. Sci.* **20**, 193–204 (2010).
22. Parton, W. J. *et al.* Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Sci. Soc. Am. J.* **51**, 1173–1179 (1987).

Author contributions
X.F. provided ecosystem modelling, statistical analysis and wrote the manuscript. B.F. designed the research. N.L. provided strategic advice and comments on the manuscript. Y.Z. and B.W. provided remotely sensed NPP and land cover for the Loess Plateau.

Additional information
Supplementary information accompanies this paper at http://www.nature.com/scientificreports

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Feng, X., Fu, B., Lu, N., Zeng, Y. & Wu, B. How ecological restoration alters ecosystem services: an analysis of carbon sequestration in China's Loess Plateau. *Sci. Rep.* **3**, 2846; DOI:10.1038/srep02846 (2013).