Vegetation restoration in dryland with shrub serves as a carbon sink: evidence from a 13-year observation at the Tengger Desert of Northern China

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Abstract

Dryland area accounts for about 40% of land area, which play a significance role on regulating the carbon sequestration variability of land. Vegetation restoration in dryland, which is a widely adopted to prevent land degradation, could potential serve as a carbon sink based on the short-term observation. However, the sustainability of the carbon sink for the revegetated ecosystem in dryland is still unknown due to the lack of the long term of the observation data. Thus, we are aiming to investigate the carbon sequestration ability of the planted vegetation in dryland area in long run. Based on the observation of the long established revegetation, we found the revegetation area serves as a carbon sink in all of the year as net ecosystem production (NEP) is positive and demonstrate a significant increasing trend by 5.65 gC m $^{-2}$ yr $^{-2}$. The increase in spring temperature, the earlier start of carbon earlier onset of carbon uptake and longer duration of carbon uptake may contribute to the emergence of a gradual trend in NEP, but the amount of annual NEP was more determined by summer precipitation. Meanwhile, our results revealed that the increasing of carbon sequestration by the revegetation is not over-consuming water resources as there is no soil water depletion. This highlights that revegetation in dryland area could serves a carbon sink in long run.

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Highlights:

- The planted shrub since 1989 in dryland area serves as carbon sink until now.

- The expansion of the planted shrub does not need to the depletion of soil water.
- The advanced carbon update period in spring and the variation of summer rainfall is the main contributor for the carbon sequestration.

Abstract:

Dryland area accounts for about 40% of land area, which play a significance role on regulating the carbon sequestration variability of land. Vegetation restoration in dryland, which is a widely adopted to prevent land degradation, could potential serve as a carbon sink based on the short-term observation. However, the sustainability of the carbon sink for the revegetated ecosystem in dryland is still unknown due to the lack of the long term of the observation data. Thus, we are aiming to investigate the carbon sequestration ability of the planted vegetation in dryland area in long run. Based on the observation of the long established revegetation, we found the revegetation area serves as a carbon sink in all of the year as net ecosystem production (NEP) is positive and demonstrate a significant increasing trend by 5.65 gC m^{-2} yr^{-2}. The increase in spring temperature, the earlier start of carbon earlier onset of carbon uptake and longer duration of carbon uptake may contribute to the emergence of a gradual trend in NEP, but the amount of annual NEP was more determined by summer precipitation. Meanwhile, our results revealed that the increasing of carbon sequestration by the revegetation is not over-consuming water resources as there is no soil water depletion. This highlights that revegetation in dryland area could serves a carbon sink in long run.

Keywords: dryland; revegetation; carbon sequestration; carbon uptake period

Introduction

Terrestrial biosphere serves as a carbon sink which can sequestrate a large portion of emitted CO_2 due to human activities (Pan et al., 2011). The net global carbon uptake by terrestrial biosphere increased significantly over the past decades and seems to increase in the near future (Ballantyne et al., 2012; Cheng et al., 2017; Keenan et al., 2016). It is worthwhile to highlight that the afforestation and ecological restoration plays a significant role in sequestrating the carbon dioxide in China and India due to vegetation restoration (Lu et al., 2018; Piao et al., 2009; Yang et al., 2022). Studies on the impact of revegetation on carbon sinks have been reported mainly in wet or semi-humid areas, and very few studies are focusing on arid areas (Yang et al., 2014; Liu et al., 2022).

The role of vegetation restoration in dryland, in terms of carbon sequestration, is largely un-known in long term (Liu et al., 2022). Although dryland afforestation can prevent desertification and increase carbon sequestration in short period in drylands (Wang et al., 2020; Yosef et al., 2018), the sustainability of vegetation restoration is largely uncertain due to a number of factors. Shrub planting in arid and semi-arid areas regions can increase the carbon sequestration capacity of these areas (Chen et al., 2018; Wang et al., 2020) and more carbon is stored in the soil (Yang et al., 2014). The above study is based on ground-based surveys (vegetation or soil sample scales) on short period and do not reflect the long-term climate change impacts on the carbon cycle. However, the carbon sequestration in long run is not sure due to the following reasons. First, the planted vegetation could lead to over-consumption of water resources (Jackson et al., 2005), especially in arid and semi-arid areas. This would lead to some negative ecological consequences such as drying of the soil, decline in groundwater (Cao S X, 2008) loss of runoff, etc. (Wilske et al., 2009). Numerous studies predicted that the large area of woody sand-binding vegetation will degrade or become extinct due to soil water depletion and underground water decreasing in sandy areas of northern China (Cao, 2008). Second, dryland is the most vulnerable regions to the effects of climate change (Huang et al., 2017). There is an increasing trend of drought in dryland area as dryland has much faster warming trend than the global average (Lian et al., 2021). This poses a challenge to the sustainability of vegetation restoration in dryland area and also to the carbon sequestration. Therefore, the stability and sustainability of the carbon sink effect of dryland vegetation restoration does not reach consensus (Liu et al., 2022).

The marginal ecosystems, semiarid savannas and shrublands, play an essential role in regulating the variability of the land CO_2 sink (Ahlstrom et al., 2015; Poulter et al., 2014; Sha et al., 2022). The variability of carbon sequestration in arid area is mainly due to the increasing variability of precipitation in the warming world (Ahlstrom et al., 2015; Poulter et al., 2014). Meanwhile, the change of growing season or carbon uptake period due to climate change also has significant influence on the carbon sequestration (Wu et al., 2013). The impact of climate warming on plant phenology was extensively investigated, especially focusing on the length of the growing season (GSL) (Piao et al., 2007; Piao et al., 2020) or the prolongation of the carbon uptake period (CUP) (Churkina et al., 2005). Overall, the relationship between annual carbon uptake and CUP is more strongly correlated than GSL (White and Nemani, 2003; Wu et al., 2012). Warmer temperatures in spring and autumn extend the period of vegetation activity, which leads to the increasing net carbon uptake period, and usually stimulates NEP (Fu et al., 2017). Longer periods of carbon uptake increase NEP in forest ecosystems, but may have no effect on non-forest ecosystems (Wu et al., 2012). Most of the above studies on the effects of climate change on NEP due to warming have been conducted in forests or grasslands, with very few studies in desert ecosystems.

As dryland accounts for 40% of land area and vegetation in dryland area could play a significant role to sequestrate carbon dioxide of atmosphere according to previous studies. Meanwhile, vegetation restoration in dryland area is a popular strategy for land degradation prevention. Hence, this study aims to investigate the carbon sequestration potential of planted vegetation in dryland and also the impact of climate change on the carbon sequestration of these planted vegetation in arid region, by taking the advantage of long-term eddy flux measurements over the stable planted vegetation in arid area.

Materials and methods

2.1 Experiment site

We selected the planted shrubs (since 1989) as the monitoring targets. It is worthwile to highlight that the vegetation coverage reaches relative stable status since the start of measurements (2009). The enhanced vegetation index (EVI) during growing season for restored vegetation area established since 1989 (see supplementary material for data sources) also show an increasing trend and also reach a steady state before the eddy flux measurement installation at 2009. It reveals that restored vegetation needs about 20 years (1989-2009) to reach a stable status. This is consistent with previous studies that EVI was a significant increase for approximately 10-20 years of vegetation establishment (ref). The dominant xerophytic shrubs in this revegetation area were A. *ordosica* (the average height of 0.6 m) and C.*korshinskii* (the average height of 1.2 m), with the shrub coverage approximate 25%.

This study site is located at the southeastern edge of the Tengger Desert in Shapotou region (37°27' N and 105deg00'E, at an altitude of 1288 m AMSL), northwest China (Figure S1). The natural vegetation of this area is dominated by *Agriophyllum squarrosum* and *Hedysarum scoparium* with a cover of about 1% (Li et al., 2004a). Groundwater level is more than 60 m which is not available by vegetation and precipitation is the only source of soil water in this area (Li et al., 2004b). Average wind velocity was 2.8 m s^{-1} in a predominantly northwesterly direction and the mean annual number of days with dust events is 122 (Liu et al., 2006).

The study area has a mean annual temperature (10@C), with extreme minimum and maximum temperature is -25.1 @C in January and 38.1 @C in July respectively (X. Li et al., 2014). According to meteorological records from the Shapotou Desert Experimental Research Station of the Chinese Academy of Science (Shapotou Station) from 1955 to 2016, the mean annual precipitation was 186 mm, about 80% of which falls between May and September (Li et al., 2018). The precipitation shows high inter-annual fluctuation, and the minimum and maximum value are 52.9 mm in 2005 (Zhang et al., 2021) and 283.4 mm in 2002 (Li et al., 2014). The annual potential evaporation is nearly 3000 mm (Li XR, 2012).

The Tengger Desert in Shapotou area was characterized by sandy, high, dense and continuous reticulate barchan dune (Figure S1). To ensure unimpeded passage of the Baotou-Lanzhou railway through the sand dunes in this area, a sand-binding vegetation protective system by planting of xerophytic shrubs was established since the 1950s (Li XR. 2005). Details of the revegetation were described by Li et al. (2004a). The revegetation area was further expanded in 1964, 1973, 1982, 1987 and 1989 using the same methods. A 500 m wide belt of sand-binding vegetation was established on the north side of the railway and a 200 m wide belt of sand-binding vegetation was established on the south side of the railway, with a total length of 16 km (Figure S1). Through nearly 50 years of development and succession, the mobile dune-dominated desert landscape transformed into a complex artificial-natural desert ecosystem (Li XR. 2005) (Figure S1).

Eddy covariance and micrometeorological measurements

An open-path eddy covariance (EC) system was installed in revegetated area in 2008. The EC system consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) and an open-path infrared gas analyzer (LI-7500, LiCor, Lincoln, NE, USA), both were mounted 4 m above the soil surface. The Li-7500 was calibrated for CO_2 and water vapor using calibration gases and a dew point generator in early April of each year. The 10 Hz raw data (Three-dimensional wind vector, sonic virtual temperature and concentrations of CO_2 and H_2O) was logged with a data logger (CR3000, Campbell Scientific, Logan).

The weather conditions were monitored synchronously. Air temperature (Ta), relative humidity were measured using HMP45C sensors (Vaisala Inc., Helsinki, Finland) and net radiation (Rn) was measured using CNR-1 (Kipp&Zonen, the Netherlands) at 4, 4 and 3m above the soil surface, respectively. Two self-calibrating soil heat flux sensors (HFP01) were installed 0.05 m below the soil surface. Soil temperature and soil water content were measured using five soil temperature sensors 109-L (Campbell Scientific Ltd., Edmonton, Alberta, Canada) and five soil water probes (EnviroSMART, Campbell Scientific Ltd., Edmonton) at the depths of 0.05, 0.10, 0.15, 0.20, 0.40m and 0.20, 0.40, 0.60, 1.0, 2.0m, respectively. Precipitation was measured by a rain gauge (TE525MM, Texas Electronics Inc., Dallas, T X, USA) at 0.5 m above ground level. The 30-min meteorological data were also recorded with the data logger (CR3000, Campbell Scientific, Logan).

2.3 Data processing

The EddyPro 6.2 software (LiCor, Lincoln, NE, USA) was used to compute the 10-Hz raw date. We used the Express Mode of EddyPro to calculation the 30-min fluxes, such as net ecosystem productivity (NEP), latent heat (H) and sensible heat (LE). These corrections include spike removal, tilt correction (secondary coordinate rotation), corrections for air density fluctuation (Webb, Pearman, & Leuning, 1980), sonic virtual temperature correction. The spectral corrections for flux losses (Moncrieff et al., 1997) is recommended for the processing of raw eddy data.

The 30-min fluxes data were processed using the standard methodologies recommended by ChinaFLUX (Yu et al., 2008; Zhang LM, 2006). The fluxes data were removed during sensor malfunction and maintenance, rain and snow events. The night-time fluxes data was filtered under low atmospheric turbulence conditions when the thresholds of friction velocity (u*) < 0.10 m s $^{-1}$ (Gao et al., 2012). During the non-growing season, due to the self-heating of the open-path CO_2/H_2O infrared sensor (Burba et al., 2008), spurious ecosystem CO $_2$ uptake were measured and negative CO_2 flux data (representing what the ecosystem uptake by the CO_2 from the atmosphere) were discarded.

For missing data, short periods of <2 h were filled by linear regression, while longer periods were replaced with mean diurnal variation with a 7-d window (Falge et al., 2001). For Larger gaps, the Michaelis–Menten equation with a 10-day moving window (Michaelis and Menten, 1913) was used to estimate the day-time NEP (NEP_{day}). Because of no photosynthesis during the night-time, the night-time NEP (NEP_{night}) was the ecosystem respiration in night time (Re_{night}). The missing Re_{night} was estimated using the enhanced Van't Hoff equation (Yu et al., 2008), which considers soil temperature at 5-cm and soil water content at 20cm. Details of the equation were described by Yu et al (2008). The daily ecosystem respiration (Re) was the sum of the RE_{night} and RE_{day}. The daily gross ecosystem productivity (GEP) was estimated used the daily NEE and daily Re.

The system energy closure ratio (defined as the ratio between the sums of turbulent and soil heat fluxes against radiant fluxes) was above 79% (Gao, et al., 2016), which indicated that flux measurements were reached moderate level of robustness (Wilson et al., 2002).

2.4 Definition and analysis of carbon uptake period

Annual NEP is strongly correction with the net carbon uptake period (CUP) (Fu et al., 2017). We used a 7-day moving average to determine the spring start day of the net carbon uptake (SCUP) and autumn end day (ECUP) of the net carbon uptake. The SCUP was the first day and EDOY was the last day when the 7-day moving average NEP>0. The duration of carbon uptake period (DCUP) was defined by the number of days between the SCUP and ECUP (Fu et al., 2017).

2.5 Statistical analysis

We used the function '*mkttest* ' in '*modifiedmk* ' package in RStudio 4.0.3 estimated the long-term trend (low frequency signal) of annual carbon flux and environmental variables. All statistical analyses were done using SPSS 23.0 software (SPSS Inc., USA), and plot was used OriginPro 2020 software (OriginPro Lab Corp., Northampton, MA).

3 Results

3.1 Interannual variation of biophysical climate factors

An increasing trend of temperature is observed. The mean annual temperature over 13-year is 11.50 ± 0.69 (mean value +- standard deviation, CV=12.86%), with 2012 being the coldest year (10.03 *C) and 2021 being the warmest (12.48 *C). Seasonal mean temperature in spring, summer, and autumn showed a non-significant increasing trend over the 13 years, and the largest increasing rate was 0.91% y^{-1}occurred in spring (Figure 2a). Annual Ta also exhibited a non-significant increasing trends over the study period with an increasing rate of 0.78 % y^{-1} (Figure 2b). Meteorological data from the Zhongwei meteorological station, approximately 20km, Shapotou during 1959-2017, show a significant increasing trend in air temperature with an annual increase rate of 0.38% y^{-1} (Figure 2Sa). Over our study period (2009-2021), the rate of increase in temperature exceeds the multi-year average rate of increase. The annual accumulative precipitation over study period (2009-2021) was 180.12+-43.67 mm (CV=24.25%) (Figure 2c). The minimum precipitation in 2013 (127.60 mm). The accumulative precipitation in spring, summer and autumn is 19.7%, 54% and 25.8% of the annual precipitation respectively. Annual and seasonal accumulative precipitation was no obvious trend during the 2009-2021 (Figure 2c, d). Precipitation data from meteorological stations in Zhongwei from 1959-2017 showed an average annual precipitation of 180 +- 54.57 mm, which is almost consistent with our results. There is not a clear trend in annual precipitation (Figure S2).

The carbon uptake period showed an increasing trend (Figure 3). The start of carbon uptake in spring (SCUP) ranges from DOY 75 to 97, the end of carbon uptake (ECUP) in autumn from DOY 289 to 321, and the duration of carbon uptake (DCUP) from 196 to 244 days. These three key indicators of carbon uptake period showed a significant multi year trends, with SCUP showing an early trend, ECUP demonstrating a delayed trend and thus DCUP revealing a continuous increasing trend. maximum value of precipitation was 253.30 mm in 2018, which was nearly twice of the

3.2 Interannual variability and trends of carbon fluxes

Annual NEP is positive and showed an increasing trend (5.65 $gC.m^{-2}$. y^{-2}) from 2009 to 2021 (p <0.05) (Figure 4). The mean NEP is 91.61+-36.17 $gC.m^{-2}.y^{-1}$ (CV 39.49%) over study period (2009-2021). The maximum value was 168.30 $gC.m^{-2}.y^{-1}$ in 2020 and the minimum value was 34.70 $gC.m^{-2}.y^{-1}$ in 2010 (Figure 4).

The mean value of accumulative NEP in spring, summer and autumn was 31.07, 60.91 and 25.31 $gC.m^{-2}$, which was account for 33.9%,66.5% and 27.6% of the annual NEP, respectively. The accumulative NEP in spring displayed a statistically significant increasing trend, with an increase rate of 3.18 $gC.m^{-2}$. y^{-2}(p <0.01) (Figure 5a), which was accounted for 56 % of the annual increase rate. There was no statistically significant trend was observed for the other season (Figure 5b, c).

NEP is determined by GEP and Re and thus we analyzed the long-term trends of GEP and Re. Both annual and spring GEP showed a statistically significant increasing trend over the 13 years (p <0.05), with an increasing rate of 8.63 and 4.65 gC.m^{-2}. y^{-2}, respectively (Figure 4, 5a), which was consistent with the trend of NEP. The annual Re was showed a non-significant increasing trend (p >0.05) (Figure 4). Re in spring, summer, and autumn did not exhibit significant increasing trend. It can be seen that the growth trend of NEP is mainly caused by the growth of GEP, especially in spring.

3.3 The relationship of NEP and biophysical climate factors

The influence of annual temperature on NEP, Re, and GEP are neglectable (Figure 6 a), and precipitation has a significant effect on Re only (Figure 6b). DCUP has strong correlation with NEP and GEP, but no statistically significant relationship with Re (Figure 6c). This reveals that the increase of DCUP leads to an increase in NEP and GEP, but has no significant effect on Re.

The relationship between NEP and biophysical climate factors varied within seasons. The spring temperature and the advanced onset of carbon uptake period leads to increase of NEP (Figure 7a), but spring precipitation has no-significant influence on NEP (Figure S3). In summer, NEP was mainly influenced by summer precipitation, which explained 48% of the variation, and was not correlated with temperature (Figure S3). The summer precipitation also has significant influence on Autumn NEP, with precipitation explaining 49% of the variation of NEP in Autumn (Figure 7b, c). NEP in autumn does not correlated with autumn temperature, precipitation, or end carbon uptake time (ECUP) (Figure S3).

4 Discussion

4.1 The carbon sequestration potential of vegetation restoration in dryland area

In this study, we found that planted vegetation in arid area showed a carbon sink not only in vegetation establishment period in the first 20 years, but also the established stable status. EVI showed a gradual increase during the first 10-20 years of vegetation restoration, with large variation in the following years (Figure 1). During stable period (since 2009), there is an increasing trend in NEP (by 5.65 gC m^{-2} yr^{-2}, $p<0.05$) and an annual increasing trend of 6.17%, associated with a significant increasing annual GEP (8.63 gC m-^{2}yr^{-2}, $p<0.05$) and slightly increasing annual Re (3.0 gC m $^{-2}$ yr^{-1}, $p>0.05$) (Figure 4). Previous field survey results show that the establishment of shrubs vegetation can not only effectively curb the development of desertification, but also increase ecosystem carbon stocks (Yang et al. 2014; Huang et al., 2014; Chen et al. 2018; Wang et al. 2020). Results from a sand fixation project in a humid area showed that the average annual carbon sequestration in the first 10 years of sand fixation vegetation establishment (from 2000 to 2010) was 158 gC.m^{-2}.y^{-1} (Lu et al., 2018), which is higher than the results from our arid artificial vegetation sand fixation area. Annual carbon sequestration rates in artificial shrub ecosystems from the southern edge of the semi-arid Mu Us Desert vary over a range of 77˜-76 g C m^{-2}yr^{-1} (Jia et al., 2016; Liu et al., 2019). Its vegetation was established for about 20-30 years (2012-2016). Compared to semi-arid artificial shrub vegetation systems, although our arid shrub system had a lower GEP in the relevant year of observation, it also had a relatively lower Re, resulting in a higher NEP than the semi-arid shrub system (Liu et al., 2019).

In natural shrub ecosystems, the annual amount of carbon sequestered by ecosystems varies considerably from region to region. Piao et al. (2009) found that it is also a very important carbon sink in China, with an average carbon sequestration of 10+-5gC.m^{-2}.y^{-1}. The saline shrub community in the Gurbantunggut desert (in arid land) were showed a small carbon sink with the annual carbon sequestration 26+-13gC.m^{-2}.y^{-1} (Liu et al., 2012, 2016) and the arid shrub ecosystem near Baja California, Mexico was found a carbon source from measured results in 2002-2008 and annual carbon sequestration -79+-117 gC.m^{-2}.y^{-1} (Bell et al., 2012). Sites in the Mojave Desert in the USA and the scrub deserts of Mexico show net carbon uptake, with carbon sink rates of 40-120 gC.m^{-2}.y^{-1}, which is relatively close to the range of carbon sink intensities in our desert shrub artificial systems which mainly due to the switch between functioning as carbon sinks or sources in wet or dry years (Bell et al., 2012; Biederman et al., 2017; Liu et al., 2016, Xie et al., 2016).

Compared with natural shrub community, the carbon fixation capacity of shrub planting vegetation in Shapotou area is higher than that of natural shrub vegetation and the inter-annual variability of carbon flux was always a carbon sink, weather in wet year or dry years. This indicates that the planting of artificial shrubs could potential enhanced the carbon sink function in desert area.

4.2 The influence of biophysical climate factors on NEP

We found that the increased spring temperature resulted in a significant advance in spring SCUP. This is consistent with the findings of Fu et al. (2017), where SCUP is mainly influenced by the temperature in spring. Both were significantly correlated with NEP in spring. The increase in spring temperature and the earlier time of carbon uptake (SCUP) led to a gradual increase in NEP in spring. Spring temperature only caused a significant increase in GEP, but not in Re (Figure 7a). At the same time, the earlier carbon uptake time had a significant effect on both GEP and Re. This may be due to an increase in early vegetation activity due to a warm spring (Wolf et al., 2016), and an earlier spring SCUP (Fu et al., 2017), which increases ecosystem productivity. In desert ecosystems, the pattern of change in Re is determined by soil respiration (Gao et al., 2015). Due to the limitation of soil moisture, increasing temperature instead decreases the rate of soil respiration (Guan et al., 2021), and therefore no significant correlation was shown between increasing temperature and Re in spring. NEP in spring was not affected by spring rainfall (Figure S3). This may be due to the fact that the legacy effects of the previous year's precipitation (Sala et al., 2012) and soil moisture carry-over from late autumn to the following spring play a key role in determining canopy development, ecosystem productivity and carbon balance (Jia et al., 2016), which may reduce the response of spring NEP to the current season's precipitation. This suggests that in desert artificial vegetation areas, temperature increases and phenological changes in spring may be more important for spring and even year-round NEP. Liu et al. (2019) also found a similar knot in semiarid shrubland. The sum of mean value of summer and autumn NEP amounts was 92.22 gC m $^{-2}$, which exceeded 90% of the total annual NEP, so that summer and autumn carbon uptake made the largest contribution to the annual carbon uptake. Summer precipitation determines the amount of NEP in summer and autumn (Figure 7c, d). Although the ECUP is significantly earlier in autumn, it is not due to autumn temperatures (Figure S3). This may be due to the fact that while ECUP is influenced by more factors such as soil moisture content and radiation, in addition to temperature (Fu et al. 2017). Neither autumn temperature nor end of carbon uptake time (ECUP) had a significant effect on NEP and GEP in autumn, but ECUP significantly affected Re. It follows that an increase in autumn carbon uptake time would be detrimental to carbon uptake in desert ecosystems.

In addition, there is no increasing trend in soil water content for both the shallow and deep layers and evapotranspiration (ET) (Figure S4). These also suggest that the increasing trend in annual NEP in the desert artificial vegetation zone may not be due to changes in vegetation EVI, and that this increasing trend is not achieved by consuming more soil water or by increasing the actual ecosystem water consumption ET.

5. Conclusion

Vegetation restoration in dryland area shows a carbon sink during the earlier establishment (˜20 years) and also the following stable period. The annual NEP range from 34.70 to 168.30 gC.m^{-2}.y^{-1} during stable periods (2009-2021), with a mean value of 91.61 +- 36.17 gC.m^{-2}.y^{-1}. The positive value of NEP reveals vegetation restoration serves as a carbon sink. The change of climate did not directly contribute to the increase of NEP as there is no increase of temperature and annual precipitation. However, the start, end and duration of carbon uptake show a significant increasing trend which leads to the significant increase in annual GEP and the insignificant increase in Re. The change of carbon uptake period play a role in the increase of the NEP. In particular, the trend of increasing NEP is most pronounced in spring, when the increase exceeds 50% of the annual NEP increase, suggesting that the gradual increase in NEP may be more determined by the spring NEP. Higher spring temperatures and earlier start of carbon uptake increase spring NEP, while summer and autumn NEP are mainly influenced by precipitation, and the end of autumn carbon uptake has no significant effect on autumn NEP.

Our conclusions suggest that desert artificial vegetation areas exhibit a continuous and gradual increase in carbon sinks 20-30 years after establishment, with increased spring temperatures, earlier onset of carbon uptake and longer duration of carbon uptake all causing an increase in carbon sinks. Our study highlights the influence of spring temperature and phenology on the carbon cycle of desert artificial vegetation, which will enhance the amount of carbon sequestration in desert artificial vegetation areas in the context of future warming, especially in spring.

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Figure captions:

Figure 1 Interannual variation in enhanced vegetation index (EVI) from 2000 to 2021. Boxes and circles represent the change in EVI before and after the establishment of the eddy correlation system respectively.

Figure 2 Interannual variation in seasonal (a) and annual (b) mean air temperature at 4 m height and seasonal (c) and annual (d) accumulative precipitation from 2009 to 2021. Spring refers to the period from March-May, summer June-August, and autumn September-November.

Figure 3 Interannual variation in the start of carbon uptake period (SCUP), end of carbon uptake period (ECUP), and duration of carbon uptake period (DCUP) from 2009 to 2021.

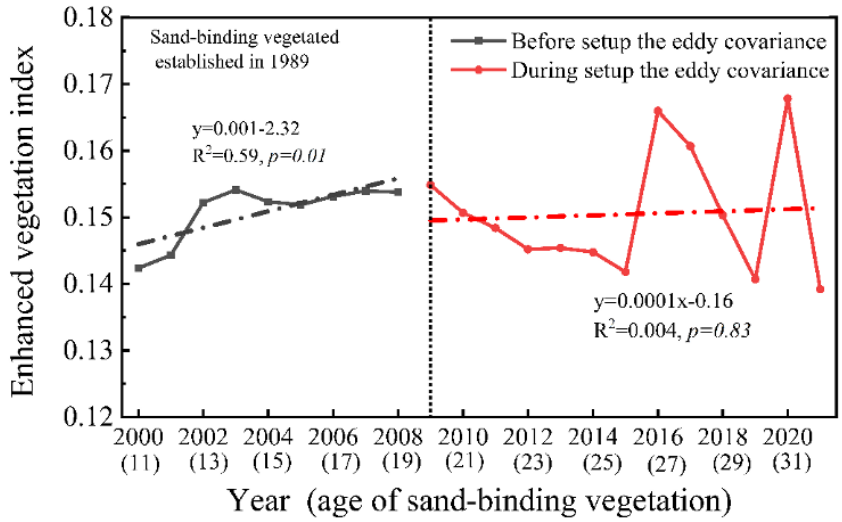
Figure 4 Interannual variation in annual gross ecosystem productivity (GEP) (close circles), ecosystem respiration (Re) (close squarest) and net ecosystem productivity (NEP) (close triangles).

Figure 5 Interannual variation in seasonal gross ecosystem productivity (GEP), ecosystem respiration (Re) and net ecosystem productivity (NEP) from 2009 to 2021. Spring refers to the period from March-May, summer June-August, and autumn September-November.

Figure 6 Relationships between carbon flux and mean annual temperature, annual precipitation and duration of carbon uptake.

Figure 7 Relationships between spring temperature (a), time of onset of carbon uptake (b) and spring carbon flux; (c) summer and (d) autumn carbon flux and summer precipitation.

Figure 1



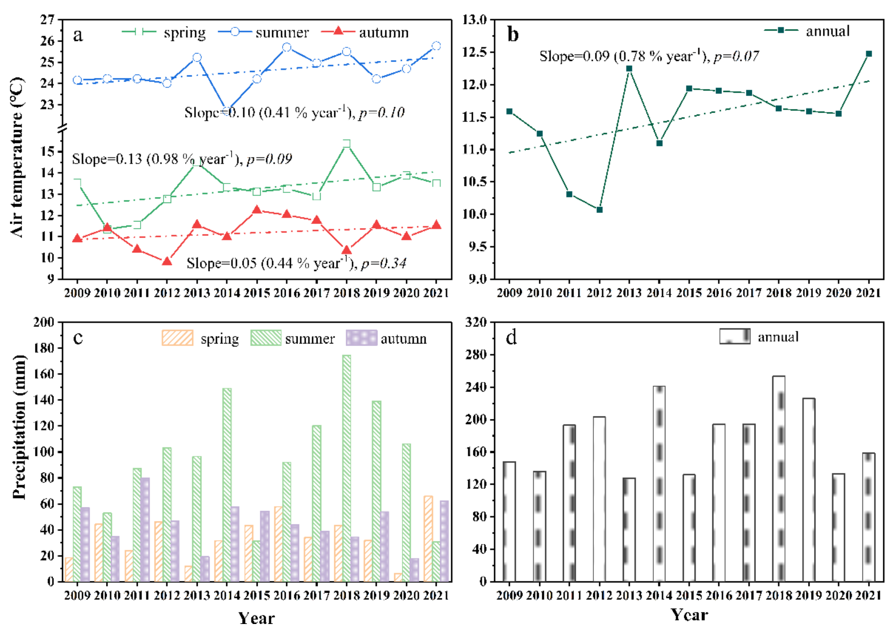


Figure 2

Figure 3

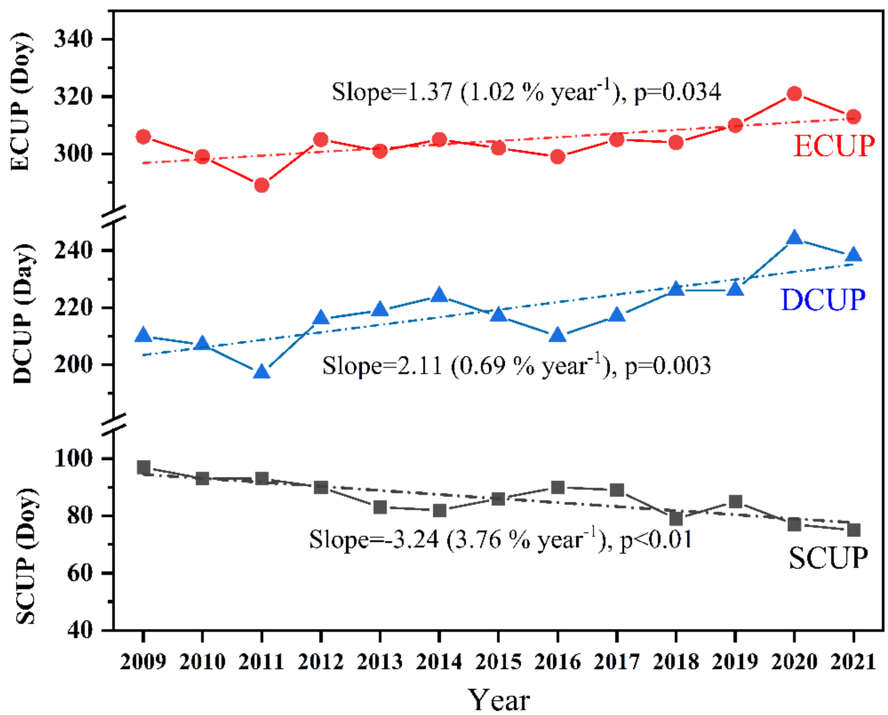
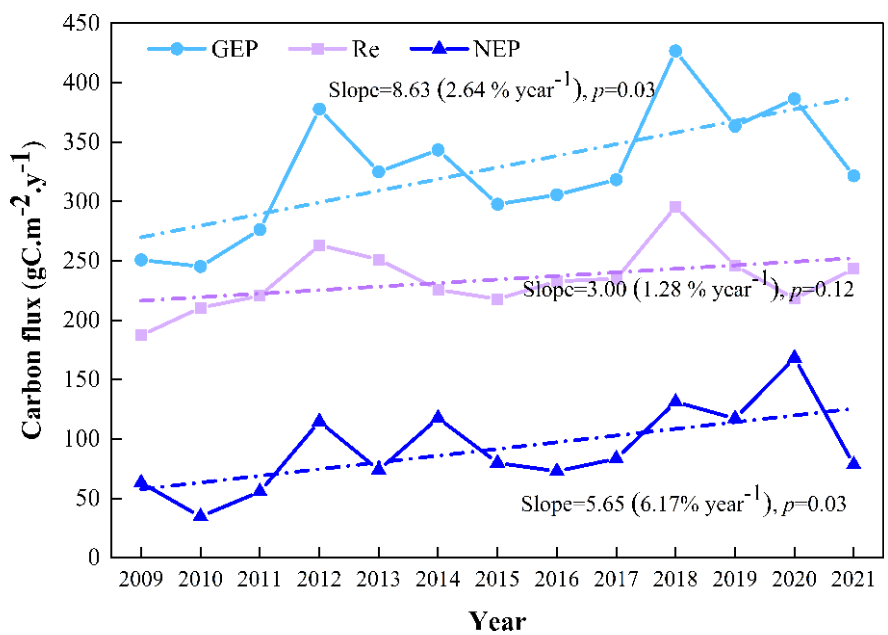

ECUP (Doy)
DCUP (Day)
SCUP (Doy)
Slope=1.37 (1.02 % year-1), p=0.034
ECUP
DCUP
Slope=2.11 (0.69 % year-1), p=0.003
Slope=-3.24 (3.76 % year-1), p<0.01
SCUP
Year

Figure 4


GEP
Re
NEP
Slope=8.63 (2.64 % year-1), p=0.03
Slope=3.00 (1.28 % year-1), p=0.12
Slope=5.65 (6.17% year-1), p=0.03
Carbon flux (gC.m-2.y-1)
Year

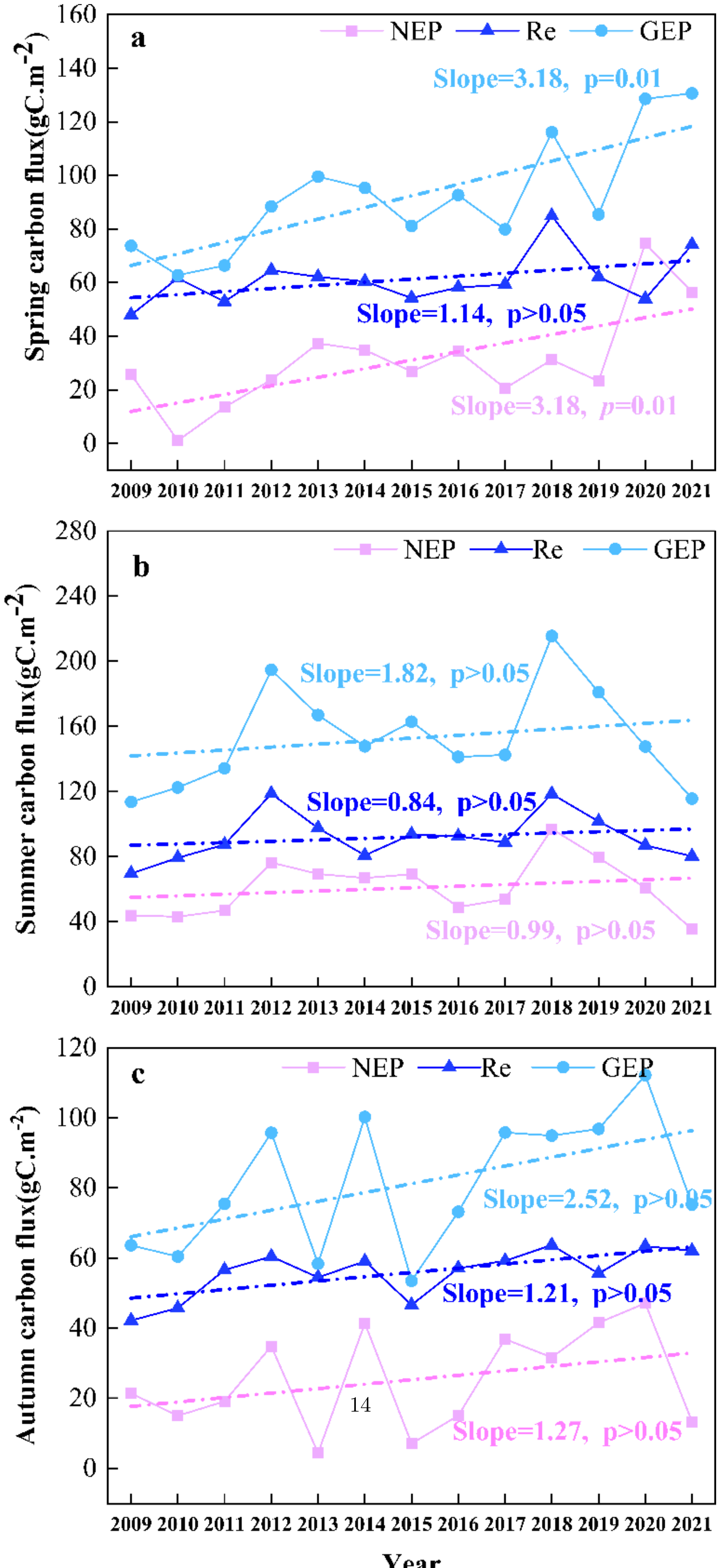

a
NEP
Re
GEP
Slope=3.18, p=0.01
Slope=1.14, p>0.05
Slope=3.18, p=0.01
Spring carbon flux(gC.m-2)
b
NEP
Re
GEP
Slope=1.82, p>0.05
Slope=0.84, p>0.05
Slope=0.99, p>0.05
Summer carbon flux(gC.m-2)
c
NEP
Re
GEP
Slope=2.52, p>0.05
Slope=1.21, p>0.05
Slope=1.27, p>0.05
Autumn carbon flux(gC.m-2)
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021
Year

Figure 5

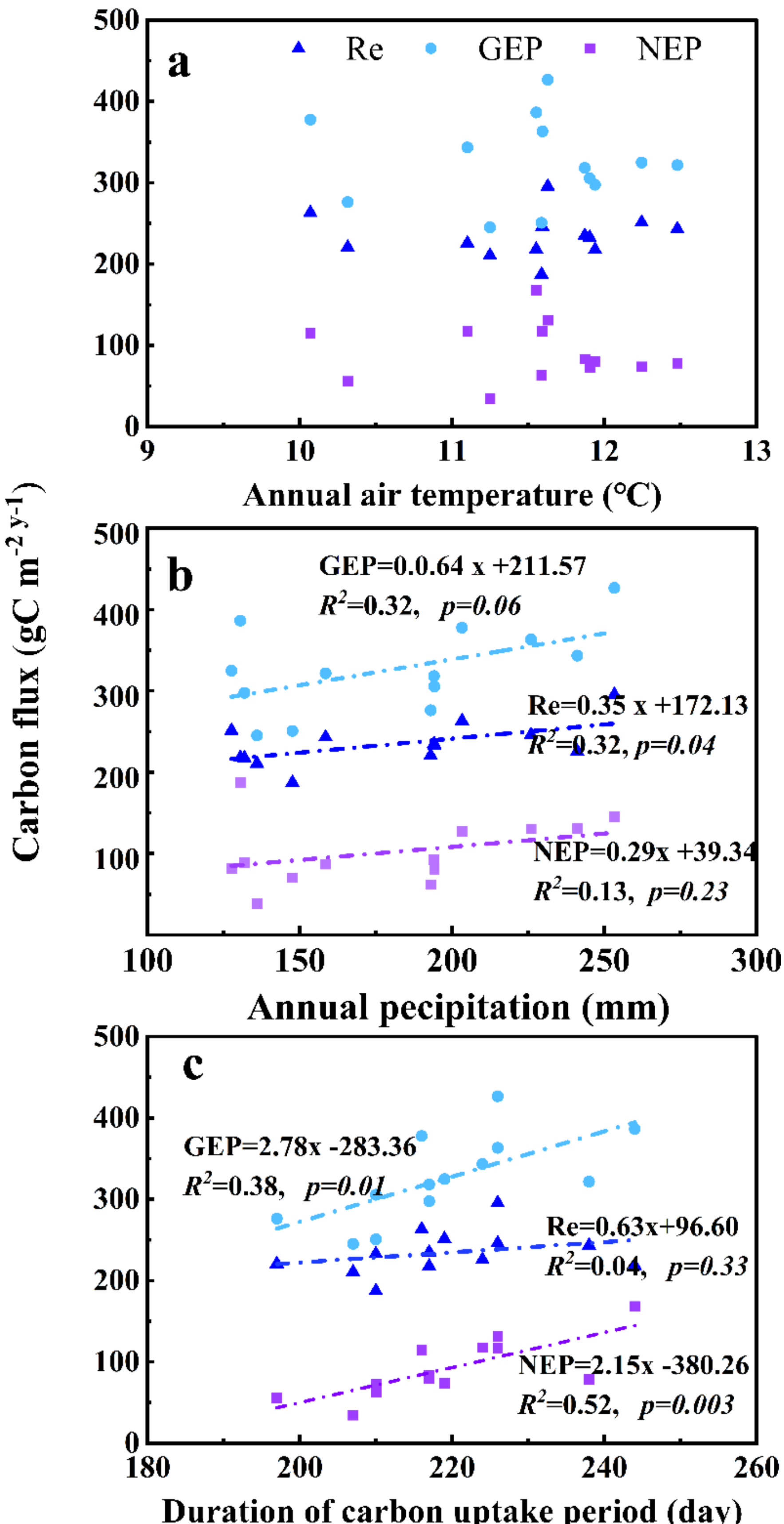

a
Re
GEP
NEP
Annual air temperature (°C)
b
GEP=0.0.64 x +211.57
R²=0.32, p=0.06
Re=0.35 x +172.13
R²=0.32, p=0.04
NEP=0.29x +39.34
R²=0.13, p=0.23
Annual pecipitation (mm)
Carbon flux (gC m-2 y-1)
c
GEP=2.78x -283.36
R²=0.38, p=0.01
Re=0.63x+96.60
R²=0.04, p=0.33
NEP=2.15x -380.26
R²=0.52, p=0.003
Duration of carbon uptake period (day)

Figure 6

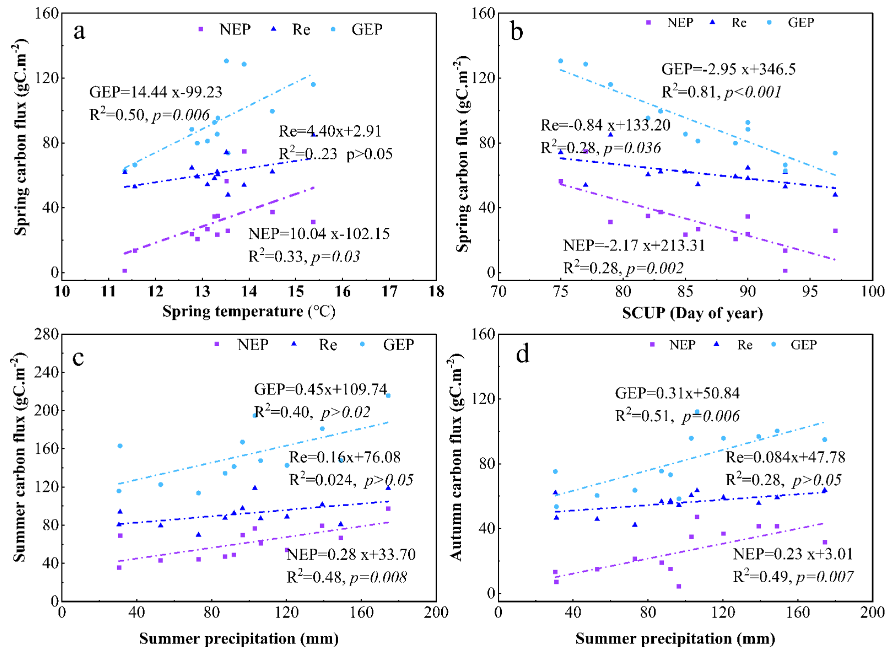


Figure 7