Altered trends in carbon uptake in China’s terrestrial ecosystems under the enhanced summer monsoon and warming hiatus

Honglin He1,2,†, Shaoqiang Wang1,2,†, Li Zhang1,2, Junbang Wang1, Xiaoli Ren1, Lei Zhou1, Shilong Piao3,4, Hao Yan5, Weimin Ju6, Fengxue Gu7, Shiyong Yu8, Yuanhe Yang9,10, Miaomiao Wang1,10, Zhongen Niu1,10, Rong Ge1,10, Huimin Yan1,2, Mei Huang1, Guoyi Zhou11, Yongfei Bai9, Zongqiang Xie9, Zhiyao Tang12, Bingfang Wu13, Leiming Zhang1,2, Nianpeng He1,2, Qiufeng Wang1,2 and Guirui Yu1,2,*

ABSTRACT

The carbon budgets in terrestrial ecosystems in China are strongly coupled with climate changes. Over the past decade, China has experienced dramatic climate changes characterized by enhanced summer monsoon and decelerated warming. However, the changes in the trends of terrestrial net ecosystem production (NEP) in China under climate changes are not well documented. Here, we used three ecosystem models to simulate the spatiotemporal variations in China’s NEP during 1982–2010 and quantify the contribution of the strengthened summer monsoon and warming hiatus to the NEP variations in four distinct climatic regions of the country. Our results revealed a decadal-scale shift in NEP from a downturn of −5.95 Tg C/yr² (reduced sink) during 1982–2000 to an upturn of 14.22 Tg C/yr² (enhanced sink) during 2000–10. This shift was essentially induced by the strengthened summer monsoon, which stimulated carbon uptake, and the warming hiatus, which lessened the decrease in the NEP trend. Compared to the contribution of 56.3% by the climate effect, atmospheric CO₂ concentration and nitrogen deposition had relatively small contributions (8.6 and 11.3%, respectively) to the shift. In conclusion, within the context of the global-warming hiatus, the strengthening of the summer monsoon is a critical climate factor that enhances carbon uptake in China due to the asymmetric response of photosynthesis and respiration. Our study not only revealed the shift in ecosystem carbon sequestration in China in recent decades, but also provides some insight for understanding ecosystem carbon dynamics in other monsoonal areas.

Keywords: climate change, Asian summer monsoon, warming hiatus, biogeochemical modeling, ecosystem carbon dynamics

INTRODUCTION

In recent years, China has become the largest carbon emitter in the world [1]. Meanwhile, the terrestrial ecosystems of China are functioning as strong carbon sinks and absorbing a significant amount of carbon dioxide (CO₂) from the atmosphere, which can partly offset the industrial carbon emissions [2,3]. Therefore, the carbon cycle of China’s terrestrial ecosystems is an important component of the global carbon budget. Modulated by the East Asian monsoon, the carbon sink of China’s terrestrial ecosystems is particularly sensitive to climate changes [4] and exhibits remarkable spatial and temporal variability [5]. Over the past decade, China has experienced a marked shift in climate-change trends. The strengthening of the East Asian summer monsoon has resulted in a dramatic change in the
spatial pattern of precipitation, with increased rainfall in North China and reduced rainfall in South China [6]. Moreover, the warming trend has substantially slowed since 1998 [7], which is at pace with the worldwide deceleration in warming known as the global-warming hiatus [8,9]. These changes in the precipitation and temperature regimes could have profound implications for carbon cycles. Studies have suggested that a shift from an increasing trend to a decreasing trend in terrestrial net ecosystem production (NEP) in China may occur in the wake of accelerated climate warming in the twentieth century [4,10]. However, little is known about the responses of terrestrial NEP in China to the dramatic changes in the climate regime that occurred at the beginning of the twenty-first century. Although recent global-scale analyses have shown enhanced terrestrial carbon uptake during the last decade with rising atmospheric CO$_2$ concentration and climate changes [11–13], the underlying mechanism is still a matter of debate. The change of terrestrial NEP in China in the latter half of the twentieth century has been well documented in previous studies [2,3,10,14,15]. However, several key questions remain unanswered under the ‘new normal’ of climate changes in the first decade of the twenty-first century. For example, will the terrestrial ecosystems of China continue to serve as a carbon sink? To what extent will the terrestrial NEP respond to current climate changes? How will the changes in NEP vary among regions? Addressing these questions is of great importance not only for improving the predictions of terrestrial carbon balance in China under the threat of future climate changes, but also for providing more accurate information to policymakers.

Under the Carbon Budget Special Project [16], we obtained in situ volumetric observational data, including 74 site years of eddy-covariance data from 11 flux towers of the Chinese Terrestrial Ecosystem Flux Observation and Research Network (ChinaFLUX) [17] and carbon stock data of 11 984 plots with geographic coordinates (Fig. 1a) from the field survey data across China [18]. These data provide a unique opportunity to validate and parameterize carbon-cycle models. In this study, three ecosystem models (CEVSA2, BEPS and TEC; see Supplementary Text 1 and Supplementary Table 1, available as Supplementary Data at NSR online) were validated and parameterized using these newly obtained data (Fig. 1b–d). These models were then used to simulate the spatial and temporal variations in terrestrial NEP in China from 1982 to 2010. Furthermore, using a map of climatic regions...
in China [19], we classified the country into four climatic regions (i.e. temperate continental, temperate monsoonal, high-cold Tibetan Plateau and subtropical–tropical monsoonal) to investigate responses of the terrestrial NEP to climate changes in different climatic regions. Our results revealed a climate-dominated shift in the terrestrial NEP trend in China in recent decades and highlighted the importance of monsoonal precipitation to this shift in the context of warming hiatus.

RESULTS

The magnitude and trends of national NEP

The ensemble mean of the modeled NEP in China’s terrestrial ecosystems showed a large spatial heterogeneity over 1982–2010, with positive values (net carbon sinks) in most areas in the east half of the country and negative values (net carbon sources) in the west parts of the country, especially in the Tibetan Plateau and Inner Mongolia (Fig. 2a). The positive values of NEP covered about 71.8% of the land area (Fig. 2b). Overall, terrestrial ecosystems in China sequestered $0.118 \pm 0.079 \text{ Pg C/yr}$ during 1982–2010, of which $0.069 \text{ Pg C/yr}$ (58.7%) were from the subtropical–tropical monsoonal region, $0.025 \text{ Pg C/yr}$ (21.0%) from the temperate monsoonal region and only small amount from Tibetan Plateau ($0.017 \text{ Pg C/yr}$, 14.3%) and temperate continental region ($0.007 \text{ Pg C/yr}$, 6.0%) (Fig. 2c).

Interestingly, terrestrial NEP of China showed a decadal-scale shift from a downward trend of $-5.95 \text{ Tg C/yr}^2$ (reduced sink) during 1982–2000 to an upward trend of $14.22 \text{ Tg C/yr}^2$ (enhanced sink) during 2000–10 (Fig. 3a). The growth rate of gross primary production (GPP) in 2000–10 was 2.1 times higher than that in 1982–2000 ($41.93$ vs $13.49 \text{ Tg C/yr}^2$; Fig. 3b), whereas the rate of ecosystem respiration (RE) increased by only 42.4% compared with that of 1982–2000 ($27.68$ vs $19.44 \text{ Tg C/yr}^2$; Fig. 3c). This asymmetric increase in GPP and RE led to an overall increase in NEP in the recent decade (2000–10), during which the precipitation trend increased and the warming trend decreased, compared to the first two decades (Fig. 3d).

NEP trends and the climatic attribution in different regions

The trend of the modeled NEP varied across the climatic regions during the two periods (Fig. 4 and Table 1). It is noteworthy that the monsoonal areas dominated the NEP trend (Table 1). Specifically, in the first two decades (1982–2000), the modeled NEP trend in the temperate monsoonal region ($-3.40 \text{ Tg C/yr}^2$) accounted for 57.1% of the downward trend in China’s NEP, whereas that in the subtropical–tropical monsoonal region ($-1.74 \text{ Tg C/yr}^2$) accounted for 29.3% ($-1.74 \text{ Tg C/yr}^2$) of this downward trend. On the other hand, in the last decade (2000–10), the temperate monsoonal region contributed 61.7% ($8.77 \text{ Tg C/yr}^2$) to the total country’s NEP trend and the subtropical–tropical monsoonal region contributed 19.3% ($2.75 \text{ Tg C/yr}^2$) to this upward trend. Compared to the monsoonal areas, the other two climatic regions played minor roles in the contribution to the national NEP trend.

The multiple regression analysis of the modeled NEP versus climate variables (i.e. temperature and precipitation) showed that the country’s NEP decreased with increasing temperature because of
the larger effect of warming on RE than on GPP (132.1 vs 70.5 Tg C/°C) and increases in precipitation enhanced NEP because of the greater stimulatory effect of water availability on GPP than on RE (252.4 vs 135.5 Tg C/100 mm) (Table 2). The sensitivity of NEP to temperature and precipitation also varied across the climatic regions. The NEP was more sensitive to precipitation in the temperate monsoonal region (57.4 Tg C/100 mm) and the continental region (62.6 Tg C/100 mm) than the other two climatic regions, due likely to the water limitation during the growing season of ecosystems in the temperate areas. At the same time, the NEP was most sensitive to temperature in the subtropical–tropical monsoonal region (−41.8 Tg C/°C).

The trends of the modeled NEP induced by climate changes in different regions, as shown in Fig. 5a and b, were determined by the sensitivity of NEP to temperature and precipitation (Table 2) as well as their variations (Fig. 5c–f). In the temperate continental climatic region, the NEP decreased at a rate of −1.03 Tg C/yr² during 1982–2000 (Table 1). The NEP trend attributed to progressive warming (−0.62 Tg C/yr²) contributed 60.5% to the change in this region (Fig. 5c), although the sensitivity of NEP to temperature was relatively low (−8.0 Tg C/°C). The NEP increased at a rate of 3.08 Tg C/yr² during 2000–10 (Table 1) and around 56.0% (1.72 Tg C/yr²) of this change was attributed to precipitation due to the high sensitivity of NEP to precipitation (Table 2) and the concurrent wetting trend (Fig. 5c).

In the temperate monsoonal region, the NEP was positively correlated with precipitation because photosynthesis showed a greater response to precipitation than RE (116.2 vs 58.8 Tg C/100 mm; see Table 2). In 1982–2000, precipitation declined progressively (Fig. 5d), which contributed 47.3% (−1.61 Tg C/yr²; Fig. 5a) to the decreasing trend of NEP in this region. However, during 2000–10, summer precipitation increased significantly (6.57 mm/yr, \( p < 0.05 \)) (Fig. 5d), which caused a rise in NEP of 3.87 Tg C/yr² (Fig. 5b) that contributed 44.2% to the NEP increase in this region.

**Figure 3.** Anomalies of carbon budgets in China’s terrestrial ecosystems during 1982–2000 and 2000–10, along with anomalies of climate data. (a) Net ecosystem production (NEP), (b) gross primary production (GPP), (c) ecosystem respiration (RE) and (d) summer precipitation and mean annual temperature. The brown lines and shaded areas in panels (a), (b) and (c) indicate the ensemble mean and 95% confidence interval of the data. The solid and dashed lines delineate the trend determined by linear regression. A positive NEP value indicates a carbon sink.

**Figure 4.** Spatial distribution of the trends in net ecosystem production (NEP) in China during (a) 1982–2000 and (b) 2000–10. Four climatic regions are illustrated to compare the differences in the NEP trends in different regions in the two periods. For details on climatic regions I, II, III and IV, see Fig. 1.
Table 1. Trends of net ecosystem production (NEP) in four climatic regions and throughout China. A positive trend in NEP indicates an increasing sink and a negative trend indicates a decreasing sink.

| Climatic region                      | 1982–2000 | 2000–10 |
|--------------------------------------|-----------|---------|
|                                      | Trend (Tg C/yr$^2$) | $R^2$    | P-value | Trend (Tg C/yr$^2$) | $R^2$    | P-value |
| Temperate continental (I)            | –1.03     | 0.06    | 0.293   | 3.08     | 0.24    | 0.128   |
| Temperate monsoonal (II)             | –3.40     | 0.18    | 0.072   | 8.77     | 0.45    | 0.023   |
| High-cold Tibetan Plateau (III)      | 0.22      | 0.02    | 0.579   | –0.38    | 0.02    | 0.675   |
| Subtropical–tropical monsoonal (IV)  | –1.74     | 0.08    | 0.231   | 2.75     | 0.03    | 0.616   |
| China                                | –5.95     | 0.17    | 0.080   | 14.22    | 0.32    | 0.069   |

Table 2. Sensitivity of gross primary production (GPP), ecosystem respiration (RE) and net ecosystem production (NEP) to temperature and precipitation during 1982–2010, as calculated by Equation 1 in the ‘Materials and methods’ section.

| Climatic region                      | Temperature (Tg C/°C) | Precipitation (Tg C/100 mm) |
|--------------------------------------|-----------------------|-----------------------------|
|                                      | GPP                   | RE                          | NEP                  |
| Temperate continental (I)            | 2.9                   | 11.0                        | –8.0                 |
| Temperate monsoonal (II)             | 17.7                  | 27.8                        | –10.1                |
| High-cold Tibetan Plateau (III)      | 16.2                  | 21.1                        | –4.9                 |
| Subtropical–tropical monsoonal (IV)  | 78.1                  | 119.8                       | –41.8                |
| China                                | 70.5                  | 132.1                       | –61.6                |

region. In the high-cold Tibetan Plateau region, NEP decreased slightly during the year of 2000–10, which was caused by a trade-off between an increase in NEP (0.05 Tg C/yr$^2$) due to increasing precipitation and a decrease in NEP (–0.13 Tg C/yr$^2$) due to warming (Fig. 5e).

In the subtropical–tropical monsoonal region, NEP was negatively correlated with temperature, because temperature variability had a greater effect on RE than on photosynthesis (119.8 vs 78.1 Tg C/°C; Table 2). During 1982–2000, the decreasing NEP attributed to the progressive warming (–1.29 Tg C/yr$^2$; Fig. 5a) accounted for 73.9% of the negative NEP trend in this region. The warming rate declined from 0.046°C/yr ($p = 0.003$) in the period of 1982–2000 to 0.029°C/yr ($p = 0.247$) in the period of 2000–10 (Fig. 5f). Because of the high sensitivity of NEP to temperature in this region, the warming hiatus reduced the negative NEP trend to −0.82 Tg C/yr$^2$ in the period of 2000–10 (Fig. 5b), suggesting that the warming hiatus has mitigated the NEP downward trend. Despite the decrease in precipitation, the NEP in this region increased at a rate of 2.75 Tg C/yr$^2$ during 2000–10 (Table 1), which was likely caused by the positive effects of nitrogen deposition [20] and afforestation [21,22] (see next section).

**DISCUSSION**

Carbon uptake in China’s terrestrial ecosystems accounted for 5.2% of the global carbon sink (2.29 Pg C/yr during 1982–2010), as reported by the Global Carbon Project [23]. This value is comparable to the carbon sink of 0.08–0.36 Pg C yr$^{-1}$ in the USA [24,25] and 0.14–0.26 Pg C/yr in Europe [26,27]. All three models used in this study revealed an increasing NEP trend during 2000–10, albeit with different rates (range: 11.94–18.16 Tg C/yr$^2$). This shift in NEP trend still exists whether we

**Contributions of different environmental factors to NEP trends**

The simulation experiments (see ‘Materials and methods’ section) revealed that climate changes were the primary factor that led to an altered NEP trend in the terrestrial ecosystems of China during 1982–2010 (Fig. 6). The trend of modeled NEP induced by climate changes shifted from negative (–8.13 Tg C/yr$^2$) during 1982–2000 to positive (3.22 Tg C/yr$^2$) during 2000–10 (Fig. 6a). This change accounted for 56.3% of the shift in the NEP trends of China between the two periods. Increasing atmospheric CO$_2$ concentration and nitrogen deposition consistently enhanced the NEP during 1982–2010, with a contribution of 1.13 and 1.59 Tg C/yr$^2$ during 1982–2000 and 2.86 and 3.87 Tg C/yr$^2$ during 2000–10 (Fig. 6b and 5c), respectively. The increase in NEP trends attributed to these two factors contributed 8.6 and 11.3% to the shift in the trend of carbon uptake, respectively. In contrast, the NEP varied by 5.09% when land-cover data in 1990, 2000 and 2010 (Fig. 6d) were used, indicating the minor impact of land-cover data on the national terrestrial carbon sink.
Contribution of precipitation and temperature to the trend in net ecosystem production (NEP) during (a) 1982–2000 and (b) 2000–10, and changes in anomalies of annual temperature and summer precipitation in four climatic regions during 1982–2010. The contribution of precipitation and temperature to NEP trends is calculated by Equation 3 in the ‘Materials and methods’ section; (c) temperate continental, (d) temperate monsoonal, (e) high-cold Tibetan Plateau and (f) subtropical–tropical monsoonal climatic regions.

Effects of multiple environmental factors on the modeled net ecosystem production (NEP) in China. (a) Climate, (b) atmospheric CO2 concentration and (c) nitrogen deposition. (d) Sensitivity of NEP to changes in land-cover data [1990, 2000 and 2010]. The dashed and solid lines in (a), (b) and (c) represent the trends determined by linear regression during 1982–2000 and 2000–10, respectively. The solid line and shaded area in (d) represents the mean and 95% confidence interval, respectively, of the NEP variations using land-cover data in 1990, 2000 and 2010.
modeled NEP in this region showed a high sensitivity to precipitation (Table 2), which is a key limiting factor of vegetation photosynthesis in the growing season [35,36]. Thus, the change in monsoonal precipitation from a decreasing to an increasing trend in this region (Fig. 5d) stimulated the ecosystem carbon uptake (see Supplementary Fig. 2c, available as Supplementary Data at NSR online). In addition, the warming hiatus suppressed the decrease in the NEP because of the larger deceleration of the RE increase than of the GPP increase, particularly in the subtropical–tropical monsoonal climatic region (Fig. 5b). In this region, the sensitivity of RE to temperature is much higher than that of GPP [37,38], which in turn led to the close association of NEP with temperature (Table 2). Therefore, more carbon gains that were driven by the enhanced summer monsoon and fewer carbon losses that were driven by the warming hiatus altered the trend in the carbon uptake of China’s terrestrial ecosystems.

In addition to climate, other environmental factors may also influence ecosystem carbon uptake in China. For example, both nitrogen deposition and atmospheric CO₂ concentration could enhance the NEP. Nitrogen deposition could stimulate photosynthesis via increasing the foliar nitrogen of plants [39] and canopy leaf area [28], thus enhancing the carbon sink. The nitrogen deposition in China during 2000–10 had a significant positive effect on the terrestrial NEP (see Supplementary Fig. 3, available as Supplementary Data at NSR online). This effect appeared to be especially strong in the subtropical monsoonal area, where the nitrogen-deposition rate was relatively high [20,40]. The rising atmospheric CO₂ concentration over the past few decades has prompted more photosynthesis than respiration, thus leading to an increase in carbon sequestration in China [4,14,28] and throughout the world [11,41]. But these two factors contributed much less to the shift in the NEP trend than did climate (Fig. 6b and c), as revealed by modeled results from simulation Experiments II, III and IV (see Supplementary Table 3, available as Supplementary Data at NSR online) in our study. Previous studies on the effect of land-cover change on the carbon budget in China have shown large uncertainties in terms of both methods and land-cover data [3,14,42,43]. Our sensitivity analyses (simulation Experiment V in Supplementary Table 3, available as Supplementary Data at NSR online) suggested that land-cover change had a minor effect on China’s terrestrial carbon sink (Fig. 6d), which might have been underestimated, since the input data LAI and FPAR used in BEPS and TEC contained some information of land-cover change. The effect of land-cover legacy on carbon uptake remained uncertain due to the scarcity and uncertainty of the historical land-cover data [44], although it may have affected the initial carbon stock [14]. The young forest age structure consistently facilitated the carbon uptake during the periods of 1982–2000 and 2000–10 [20,45]; thus, it played a minor role in shifting the NEP trend. Overall, it is clear that the consideration of the concurrent changes in non-climate factors did not undermine the importance of the enhanced summer monsoon and the warming hiatus in shifting the NEP trend from the period of 1982–2000 to 2000–10.

To the best of our knowledge, this study provides the first attempt to understand the role of climate changes in shifting the trend in terrestrial NEP of China in recent decades. Our results showed that the enhanced East Asian summer monsoon could stimulate carbon uptake in water-limited ecosystems by increasing precipitation in North China and the warming hiatus could cause a slowdown in the NEP downward trend in areas where the NEP was negatively correlated with temperature. This finding indicates that the enhanced Asian summer monsoon played a critical role in the acceleration of carbon uptake in China. Our study provides some insight for carbon sequestration analyses in other monsoonal areas worldwide. Furthermore, the East Asian summer monsoon has been projected to enhance in the future [46,47]. The IPCC Fifth Assessment Report indicated that the monsoonal precipitation will increase, as revealed by most (≥ 85%) CMIP5 models [48], although the probability of the persistence of the warming hiatus is lower than 25% [49,50]. This uncertainty poses a challenge to the prediction of the future carbon sequestration trend in China’s terrestrial ecosystems.

**MATERIALS AND METHODS**

**Model description**

We used three models, namely CEVSA2 [40], BEPS [51] and TEC [52] (see Supplementary Text 1 and Supplementary Table 1, available as Supplementary Data at NSR online), to simulate the spatial and temporal variations in terrestrial NEP in China. These models have been well validated at the site scale in previous studies (see Supplementary Table 2, available as Supplementary Data at NSR online) and have been widely used to estimate carbon and water fluxes on regional and global scales, especially in China [4,40,51–53]. In this study, all models used the same driving data, including climate, land cover and soil texture. The ensemble mean of carbon fluxes simulated by these models was used to analyse the changes in terrestrial NEP trend in China during 1982–2010.
Model input data

Climate data were interpolated from the observations at 1098 meteorological stations [54]. Land-cover data were generated from the China-Cover dataset [55]. Soil-texture data were retrieved from the Food and Agriculture Organization’s Harmonized World Soil Database (FAO HWSD). FPAR and LAI were satellite-derived Global Inventory Modeling and Mapping Studies (GIMMS) FPAR3g [56] and Global Mapping (GLOBMAP) LAI datasets [57]. Nitrogen-deposition data were produced through relating nitrogen deposition to precipitation, nitrogen fertilizer and fuel consumption [40]. Atmospheric CO2 concentration data were from the Mauna Loa CO2 dataset and historical CO2 dataset (http://www.co2.earth). For details, see Supplementary Text 3, available as Supplementary Data at NSR online.

Model evaluation

To make the modeled carbon-pool sizes consistent with new observations, we used inventory data of vegetation and soil carbon density from 11 984 plots (Fig. 1a) collected from the field survey data across three natural vegetation groups (forests, grasslands and shrublands) in China [18] to adjust the carbon pools after spin-up for CEVSAA2 and TEC and to calibrate the potential decomposition rates of the slow and passive soil organic carbon pools for BEPS. The eddy-covariance flux data, collected at five forest sites, five grassland sites and one cropland site (74 site years) of ChinaFLUX (Fig. 1b; see Supplementary Table 4, available as Supplementary Data at NSR online), were used to validate the modeled carbon fluxes at the grid cell level. Compared with the flux measurements, the mean values of the modeled GPP, RE and NEP explained 69, 74 and 38%, respectively, of the seasonal variations in the observed fluxes on average (Fig. 1b; see Supplementary Fig. 4, available as Supplementary Data at NSR online). Moreover, the means of the modeled vegetation and soil carbon-pool sizes were consistent with the inventory data (Fig. 1c and d; see Supplementary Fig. 5, available as Supplementary Data at NSR online) and the modeled total national carbon stocks in vegetation and soil were consistent with other studies (see Supplementary Table 5, available as Supplementary Data at NSR online).

Model simulation experiments

To quantify the effects of climate, atmospheric CO2 concentration, nitrogen deposition and land cover on the shift of the terrestrial NEP trend in China, we designed and conducted five simulation experiments (see Supplementary Table 3, available as Supplementary Data at NSR online). In Experiment I, the models were driven by a constant CO2 concentration and a long-term averaged climate. Experiment II was the same as Experiment I, but it was driven by realistic climate data. The difference between the modeled NEP in these two experiments represented the effect of climate change on terrestrial NEP. Experiment III was the same as Experiment II, but it was driven by the time-varying CO2 data. The CO2 fertilization effect was defined by the difference between the modeled NEP in Experiments II and III. Experiment IV was the same as Experiment III but included nitrogen-deposition data. The effect of nitrogen deposition on terrestrial NEP was defined by the difference between the modeled NEP in Experiments II and IV. Experiment V was designed to investigate the effect of land cover on the NEP by conducting a sensitivity analysis using land-cover data in 1990, 2000 and 2010.

Response of carbon fluxes to climate variables

We estimated the responses of GPP, RE and NEP to precipitation and temperature over the past three decades using a multiple regression approach [58]:

\[ y' = \delta_{\text{int}} \times P' + \gamma_{\text{int}} \times T' + \varepsilon \]  

(1)

where \( y' \) is the detrended anomaly of the ensemble mean of modeled GPP, RE and NEP; \( P' \) and \( T' \) are the detrended anomalies of precipitation and temperature, respectively; \( \delta_{\text{int}} \) and \( \gamma_{\text{int}} \) represent the sensitivity of carbon fluxes to climate variables; and \( \varepsilon \) is the residual error.

Contribution of precipitation and temperature to the NEP trends

The NEP in all climatic regions except the high-cold Tibetan Plateau climatic region had significant linear relationships with precipitation and temperature (Equation 2; see Supplementary Table 6, available as Supplementary Data at NSR online). Thus, the contributions \( (f_i) \) of precipitation \( (X_P) \) and temperature \( (X_T) \) to the trend of NEP \( (Y) \) (Equation 3) are defined as the rate of the product of the predictor variable (i.e. \( X_i \)) and its regression coefficient (i.e. \( b_i \)) in the multiple linear regression equation (Equation 2):

\[ Y = b_0 + b_P \times X_P + b_T \times X_T + \varepsilon \]  

(2)

\[ f_i = d (b_i \times X_i) / dt, i = P, T \]  

(3)
where $Y$ is the mean NEP modeled by CEVSA2, BEPS and TEC; $t$ is the year from 1982 to 2010; $b_i$ is the regression coefficient for precipitation and temperature; $b_{ij}$ is the constant term; and $\epsilon$ is the residual error.

**SUPPLEMENTARY DATA**

Supplementary data are available at NSR online.

**ACKNOWLEDGEMENTS**

We are grateful to all the 1000+ field investigators for collecting the vegetation and soil carbon stock data. We thank Dr. F.S. Chapin III for his valuable advice and careful editing of the manuscript, Dr. Martin Jung for providing the global net ecosystem exchange dataset based on the eddy covariance observations and Dr. Hanqin Tian for his constructive comments.

**AUTHOR CONTRIBUTIONS**

G.Y., H.H. and S.W. designed the research; Li Z., J.W., X.R., Lei Z., Hao Y., M.W., Z.N., R.G., M.H., Huimin Y., W.J., F.G., G.Z., Y.B., Z.X., B.W., Leiming Z., Z.T., N.H., Q.W., M.W., Z.N. and R.G. collected the data; H.H., S.W., Li Z., J.W., X.R., Lei Z. and M.H. performed data analyses; H.H., S.W., Li Z., J.W., X.R., Lei Z., S.Y., Y.Y., S.P. and G.Y. wrote the paper.

Conflict of interest statement. None declared.

**REFERENCES**

1. Liu Z, Guan D and Crawford-Brown D et al. A low-carbon road map for China. *Nature* 2013; 500: 143–5.
2. Fang JY, Guo ZD and Piao SL et al. Terrestrial vegetation carbon sinks in China, 1981–2000. *Sci China Ser D* 2007; 50: 1341–50.
3. Piao SL, Fang JY and Ciais P et al. The carbon balance of terrestrial ecosystems in China. *Nature* 2009; 458: 1009–13.
4. Cao MK, Prince SD and Li KR et al. Response of terrestrial carbon uptake to climate interannual variability in China. *Glob Change Biol* 2003; 9: 536–46.
5. Yu GR, Zhu XJ and Fu YL et al. Spatial patterns and climate drivers of carbon fluxes in terrestrial ecosystems of China. *Glob Change Biol* 2013; 19: 798–810.
6. Piao SL, Ciais P and Huang Y et al. The impacts of climate change on water resources and agriculture in China. *Nature* 2010; 467: 43–51.
7. Ding YH, Liu YJ and Liang SJ et al. Interdecadal variability of the east asian winter monsoon and its possible links to global climate change. *J Meteorol Res* 2014; 28: 693–713.
8. IPCC. Summary for policymakers. In: Stocker TF, Qin D and Plattner GK et al. (eds). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press, 2013, 3–29.
9. Fyfe JC, Meahl GA and England MH et al. Making sense of the early-2000s warming slowdown. *Nat Clim Change* 2016; 6: 224–8.
10. Mu Q, Zhao M and Running SW et al. Contribution of increasing CO$_2$ and climate change to the carbon cycle in China’s ecosystems. *J Geophys Res* 2008; 113: G01018.
11. Keenan TF, Prentice IC and Canadell JG et al. Recent pause in the growth rate of atmospheric CO$_2$ due to enhanced terrestrial carbon uptake. *Nat Commun* 2016; 7: 13428.
12. Sitch S, Friedlingstein P and Gruber N et al. Recent trends and drivers of regional sources and sinks of carbon dioxide. *Biogeoosciences* 2015; 12: 653–79.
13. Ballantyne A, Smith W and Anderegg W et al. Accelerating net terrestrial carbon uptake during the warming hiatus due to reduced respiration. *Nat Clim Change* 2017; 7: 148–52.
14. Tian H, Melillo J and Lu C et al. China’s terrestrial carbon balance: contributions from multiple global change factors. *Global Biogeochem Cycles* 2011; 25: GB1007.
15. Tao FL and Zhang Z. Dynamic responses of terrestrial ecosystems structure and function to climate change in China. *J Geophys Res* 2010; 115: G03003.
16. Fang JY, Yu GR and Liu LL et al. Climate change, human impacts, and carbon sequestration in China. *Proc Natl Acad Sci USA* 2018; 115: 4015–20.
17. Yu GR, Ren W and Chen Z et al. Construction and progress of Chinese terrestrial ecosystem carbon, nitrogen and water fluxes coordinated observation. *J Geogr Sci* 2016; 26: 803–26.
18. Tang X, Zhao X and Bai YF et al. Carbon pools in China’s terrestrial ecosystems: new estimates based on an intensive field survey. *Proc Natl Acad Sci USA* 2018; 115: 4021–6.
19. Editorial Committee. The 3rd National Assessment Report of Climatic Changes (in Chinese). Beijing: Science Press, 2015.
20. Yu GR, Chen Z and Piao SL et al. High carbon dioxide uptake by subtropical forest ecosystems in the East Asian monsoon region. *Proc Natl Acad Sci USA* 2014; 111: 4910–5.
21. Li P, Zhu J and Hu H et al. The relative contributions of forest growth and areal expansion to forest biomass carbon. *Biogeoosciences* 2016; 13: 375–88.
22. Lu F, Hu HF and Sun WJ et al. Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *Proc Natl Acad Sci USA* 2018; 115: 4039–44.
23. Le Quere C, Andrew RM and Canadell JG et al. Global carbon budget 2016. *Earth Syst Sci Data* 2016; 8: 605–49.
24. Schimel D, Melillo J and Tian HQ et al. Contribution of increasing CO$_2$ and climate to carbon storage by ecosystems in the United States. *Science* 2000; 287: 2004–6.
25. Hayes DJ, Turner DP and Stinson G et al. Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data. *Glob Change Biol* 2012; 18: 1282–99.
26. Schulze ED, Luyssaert S and Ciais P et al. Importance of methane and nitrous oxide for Europe’s terrestrial greenhouse-gas balance. *Nat Geosci* 2009; 2: 842–50.
27. Janssens IA, Freibauer A and Ciais P et al. Europe’s terrestrial biomass absorbs 7 to 12% of European anthropogenic CO2 emissions. *Science* 2003; 300: 1538–42.
28. Piao SL, Yin GD and Tan JG et al. Detection and attribution of vegetation greening trend in China over the last 30 years. *Glob Change Biol* 2015; 21: 1601–8.
29. Liu XJ, Zhang Y and Han WX et al. The strengthening East Asia summer monsoon since the early 1990s. *Chin Sci Bull* 2012; 57: 1553–8.
30. Ahlstrom A, Raupach MR and Schurgers G et al. The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink. *Science* 2015; 348: 262–3.
31. Zhang H, Chen B and vdl Laan-Luijkx et al. Net terrestrial CO2 exchange over China during 2001–2010 estimated with an ensemble data assimilation system for atmospheric CO2. *J Geophys Res: Atmospheres* 2014; 119: 3500–15.
32. Liu HW, Zhou TJ and Zhu YX et al. The strengthening East Asian summer monsoon during recent decades. *Sci Bull* 2015; 60: 1222–4.
33. Zhou TJ, Gong DY and Li J et al. Detecting and understanding the multi-decadal variability of the East Asian Summer Monsoon: recent progress and state of affairs. *metz* 2009; 18: 455–67.
34. Poulter B, Frank D and Ciais P et al. Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle. *Nature* 2014; 509: 600–3.
35. Ahlstrom A, Raupach MR and Schurgers G et al. The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink. *Science* 2015; 348: 262–3.
36. Jang M, Reichstein M and Margolis HA et al. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *J Geophys Res* 2011; 116: G00J7.
37. Chevallier F, Ciais P and Conway T et al. CO2 surface fluxes at grid point scale estimated from a global 21 year reanalysis of atmospheric measurements. *J Geophys Res* 2010; 115: D21307.
38. Bao G. Projected changes in Asian Summer Monsoon in RCP scenarios of CMIP5. *Atmos Oceanic Sci Lett* 2012; 05: 43–8.
39. Houghton RA and Hackler JL. Sources and sinks of carbon from land-use change in China. *Global Biogeochem Cycles* 2003; 17.
40. Liu ML and Tian HQ. China’s land cover and land use change from 1700 to 2005: estimations from high-resolution satellite data and historical archives. *Global Biogeochem Cycles* 2010; 24: GB3003.
41. Liu Y, Zhou Y and Ju W et al. Impacts of droughts on carbon sequestration by China’s terrestrial ecosystems from 2000 to 2011. *Biogeosciences* 2014; 11: 2583–99.
42. Wang SQ, Zhou L and Chen JM et al. Quantifying the likelihood of a continued hiatus in global warming. *Nat Clim Change* 2015; 5: 337–42.
43. Wang SQ, Zhou L and Chen JM et al. High-resolution satellite data and historical archives. *Remote Sens Environ* 2012; 124: 581–95.