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Ecological restoration and rising CO\textsubscript{2} enhance the carbon sink, counteracting climate change in northeastern China

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Abstract

The impact of climate change, rising CO\textsubscript{2}, land-use/land-cover change and land management on the carbon cycle in terrestrial ecosystems has been widely reported. However, only rarely have studies been conducted to clarify the impact of climate change and rising CO\textsubscript{2} on the carbon sink contributed by ecological restoration projects (ERPs). To better understand the impact of climate change and rising CO\textsubscript{2} on ERPs, we took the Beijing–Tianjin Sand Source Control Project zone as an example to set up different scenarios to distinguish the confounding effects of these factors on the regional carbon budget based on a remote sensing data-driven model. Compared with business as usual, our results show that climate change caused a carbon loss of 78.97 Tg C. On the contrary, ERPs contributed a carbon sink of approximately 199.88 Tg C in forest and grassland. Furthermore, rising CO\textsubscript{2} also contributed an additional carbon sink of 107.80 Tg C. This study distinguished the individual effects of different factors, and clarified the net carbon sink contributed by ERPs and rising CO\textsubscript{2} and their significance for enhancing the regional carbon sink and reversing the adverse effects of climate change on the carbon sink. Furthermore, ERPs can sequester carbon more effectively and faster compared with rising atmospheric CO\textsubscript{2} concentration.

1. Introduction

Terrestrial ecosystems are critical components of the earth system that mitigate CO\textsubscript{2} emissions from fossil fuels and the associated global warming (Tian et al 2021). These ecosystems have absorbed \textasciitilde 30% of anthropogenic carbon emissions from fossil fuels (Friedlingstein et al 2019). In recent decades, ecosystems have suffered serious degradation owing to disturbance by humans and climate change (Mitchard 2018, Santos et al 2020). Previous studies have demonstrated that ecological restoration projects (ERPs) have made a significant contribution to improving degraded ecosystems and enhancing carbon sequestration (Lu et al 2018, Erbaugh et al 2020, Tong et al 2020). Meanwhile, climate change has also had an impact on the carbon cycle and thus affects the improvement of carbon sinkage by ERPs. In addition, rising CO\textsubscript{2} has also played a great role in strengthening the carbon sink (Dusenge et al 2019, Walker et al 2021). However, few studies have distinguished the respective impacts of these factors on carbon sinks.

In the past century, economic development and population growth have induced unsustainable land development, and management has caused continuous land degradation and carbon loss. Land-use/land-cover (LULC) change has induced the loss of approximately 205 ± 60 Gt C in the form of emissions into the atmosphere globally from 1850 to 2019 (Friedlingstein et al 2019). Meanwhile, forest fires induced by poor management, insect pests, timber harvesting, fuelwood harvesting and mining caused the loss of 2.03 Pg C in areas without LULC change from 1990 to 2010 (Lai et al 2016). These disturbances offset approximately 32.1% of the forest biomass carbon sink (Liu et al 2020). In recent decades, ERPs have been implemented worldwide on different scales to promote ecosystem quality and prevent ecosystem degradation (Mitchard 2018,
Santos et al 2020, Zhou et al 2020a). Measures and practices included in ERPs have increased the area of forest and grassland and promote the quality of current forest and grassland by reducing the disturbance from logging, grazing, pests and diseases (Lu et al 2018, Liu et al 2020). These measures and practices have accelerated photosynthesis to take up more CO\(_2\) and induce greater input of soil organic matter from leaf litter and roots (Paul et al 2002, Deng et al 2017, Heinrich et al 2021). In addition, ERPs that have induced increased vegetation coverage have also reduced carbon loss by decreasing soil erosion (Lal 2003, Chirino et al 2006). Among such projects globally, the spatial scale and timespan of China’s ERPs are the largest and most well-established (Lu et al 2018). Satellite imagery shows that these ERPs have induced LULC changes and that 42% of the greening of the Earth’s surface in recent decades has occurred in China (Chen et al 2019). Furthermore, China’s ERPs have been reported to contribute over half of the regional ecosystem carbon sink (Lu et al 2018), and in forests approximately a quarter of the carbon sink can be attributed to optimized management (Liu et al 2020). Planted trees will sequester more carbon with aging in later decades (Mora et al 2018). The continuing increase in height and leaf amount promotes them to take up more CO\(_2\) with the passage of time (Larjavaara 2014, Stephenson et al 2014). Thus, ERPs will make a greater contribution to the carbon sink in later years. In grassland, comprehensive measures including enclosure, light grazing and grazing exclusion implemented in grassland have also been reported to be effective practices to restore degraded grasslands and improve the carbon stock (Hu et al 2016, Deng et al 2017, Yu et al 2019). Although carbon costs and leakage will offset part of the carbon sink contributions from ERPs, these negative effects gradually weaken as newly planted vegetation grows (Liu et al 2019).

In addition, climate change has become one of the most critical driving factors changing the carbon cycle (Sleeter et al 2019, Pan et al 2020). The carbon sequestration contributed by ERPs certainly suffers from the unignorable positive or negative effects of climate change. Global climate warming has caused the average land surface air temperature to rise by 1.31 °C–1.51 °C between 1880 and 2019 (IPCC 2019). This change probably shortens the turnover time of carbon in land ecosystems and causes more uncertainties in estimates of carbon sequestration (Carvalhais et al 2014). In tropical areas, rising temperatures and reduced precipitation have led to a die-off of forests and increased carbon emissions (Mitchard 2018). In mid- and high-latitude areas, rising temperatures can prolong the growth period of vegetation, allowing the absorption of more CO\(_2\) (Post et al 2018). Unexpectedly, these effects are probably limited due to the availability of nitrogen and phosphorus (Wieder et al 2015). In addition, a warming climate may increase soil respiration, accelerating decomposition by soil microorganisms and causing more carbon loss, especially in arid and semiarid zones (Ren et al 2020, Xu et al 2015, Pan et al 2020). A warmer and drier climate may cause severe drought, which leads to more wildfires and insect pests (Chen et al 2020, Quan et al 2019, Lasslop et al 2020, Anderegg et al 2020). These changes probably cause a decline in the growth and survival rates of vegetation (Schlaepfer et al 2017, Cao et al 2018). Therefore, it is still uncertain whether climate change is beneficial or harmful for strengthening the carbon sequestration effect.

Rising CO\(_2\) has also been demonstrated to increase leaf-scale photosynthesis and intrinsic water-use efficiency to improve productivity (Walker et al 2021). It was deemed to be the decisive factor that has driven the significant increase in the carbon sink of global terrestrial ecosystems in recent decades (Zhu et al 2016, Wang et al 2020). However, prior studies found a declining response of the rate of vegetation carbon uptake to CO\(_2\), probably suggesting that the positive effect of increasing CO\(_2\) on the vegetation carbon sink would decrease (Peñuelas et al 2017, Wang et al 2020). Thus, whether rising CO\(_2\) will continue to promote the carbon sink in the future is uncertain.

To quantify the impact of climate change, rising CO\(_2\) and ERPs on carbon sequestration in areas where ERPs have been undertaken, a case study was conducted in the Beijing–Tianjin Sand Source Control Project (BTSSCP) zone. The BTSSCP zone is in an arid and semiarid region that is sensitive to climate change and rising CO\(_2\) which provided us with a suitable area to conduct our research. The goals of this study are (a) to understand the temporal–spatial dynamics of carbon sinks in the BTSSCP zone and (b) to analyze the respective effects of various factors on carbon sinks across different ecosystems.

2. Material and methods

2.1. Study area and the BTSSCP

The BTSSCP zone is located in an arid and semiarid area in northern China and covers approximately 458 × 10\(^3\) km\(^2\) (figure 1(a)). It is located north of Beijing and suffers from the influence of the Siberian monsoon in the winter (Zhou et al 2020b). This region is characterized by a plateau, plains and mountains. The western, northwestern and northern portions of this area are located on the central Inner Mongolian Plateau, while the southeast portions are plains. There are mountains in the middle of the plains and plateau regions (Wu et al 2013). The annual average temperature is approximately 7.5 °C. More than 60% of the total annual precipitation falls in the rainy season (months 6–8) and decreases from
Spatial distribution of (a) different LULCs in the BTSSCP zone; (b) LULC change between 2001 and 2019. (c) Annual precipitation and average temperature change from 2001 to 2019. (d) Twelve-month standardized precipitation–evapotranspiration index (SPEI) and area ratio (%) of drought (SPEI < −1.5) in the BTSSCP zone during 2001–2019. (e) Change in the normalized difference vegetation index (NDVI) from 2001 to 2019.

450 mm to 150 mm from southeast to northwest (Shan et al. 2015). From 2001 to 2019, the annual average temperature did not exhibit a significant trend during the entire period (figure 1(c)). Conversely, the annual precipitation increased significantly at a rate of 4.26 mm yr⁻¹ (p < 0.05). Except for precipitation, local vegetation also obtains its water supply from snow meltwater, which determines vegetation growth (Peng et al. 2010, Sa et al. 2021). Although the increased precipitation relieved the occurrence of drought, it was continued based on the 12-month standardized precipitation–evapotranspiration index (SPEI) for 2001–2019 (figure 1(d)).

In recent decades, Beijing has suffered from severe sandstorms owing to ecosystem degradation induced by grazing and vegetation destruction (Liu et al. 2019). To alleviate the risk of sandstorms, the Chinese government started the BTSSCP in 2001. The goal of this project was to reduce dust hazards by rebuilding and protecting forests and grass. This project covers five provinces (Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia) and 75 counties (Lu et al. 2018). Measures such as forest enclosure, afforestation, conversion of croplands to forests and grassland management are included in the BTSSCP (Liu et al. 2019, Zhou et al. 2020b). These measures induced the local landscape to experience substantial changes. The normalized difference vegetation index (NDVI) significantly increased (p < 0.05) at a rate of 0.0028 yr⁻¹ (figure 1(e); appendix S3, figure S2 available online at stacks.iop.org/ERL/17/014002/mmedia). The area of the forest increased by 23.10% (9994 km²) (appendix S3, table S1). Increased forests were mostly converted from grassland, cropland and barren land, mainly in the southeast of the BTSSCP zone (figure 1(b)). Meanwhile, the areas of grassland increased by 0.42% (1359 km²) (appendix S3, table S1). For more detail please refer to appendix S1.
2.2. Methodology for carbon sink analysis

2.2.1. Estimation of the carbon sink

In this study, we estimated the carbon sink based on net ecosystem productivity (NEP), which was calculated from the net primary productivity (NPP) minus the soil heterotrophic respiration (Rh) (equation (1)); the workflow for calculating NEP is described in figure 2.

\[ \text{NEP} = \text{NPP} - \text{Rh}. \]  

NPP was calculated by the CASA model (Potter et al. 1993, 2003, Zhang et al. 2014), which is a light-use efficiency model that considers different environmental factors (equation (2)).

\[ \text{NPP} = \text{APAR} \times \varepsilon = (\text{RAD} \times \text{FPAR} \times 0.45) \times (\varepsilon_{\text{max}} \times T_{\varepsilon1} \times T_{\varepsilon2} \times W_e). \]  

Here NPP is the product of absorbed photosynthetically active radiation (APAR) and actual light use efficiency (\( \varepsilon \)), RAD is total shortwave solar radiation (MJ m\(^{-2}\)), where 0.45 is the fraction of RAD within the 400–700 nm spectral range that can be used for photosynthesis (Campbell 1977), FPAR is the fraction of APAR, which is linearly related to the NDVI and can be calculated by equation (3), \( \varepsilon_{\text{max}} \) is the potential light use efficiency, and its use here in different biomes was verified according to a previous study in China (Zhu et al. 2007), \( T_{\varepsilon1} \) and \( T_{\varepsilon2} \) are two temperature parameters accounting for temperature stress on plants and adaptation of plants to local climate conditions, and \( W_e \) is the parameter of soil water stress and is calculated according to equation (4).

\[ \varepsilon = \frac{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}} \times (\text{FPAR}_{\text{max}} - \text{FPAR}_{\text{min}}) + \text{FPAR}_{\text{min}}. \]  

where NDVI\(_{\text{max}}\) and NDVI\(_{\text{min}}\) are the NDVI values for pixels with full vegetation coverage and no vegetation coverage, respectively, and FPAR\(_{\text{max}}\) and FPAR\(_{\text{min}}\) are the maximum and the minimum FPAR, respectively.

\[ W_e = 0.5 + 0.5 \times \text{WSI} = 0.5 + 0.5 \times \frac{\text{ET}}{\text{PET}}. \]  

where WSI is the water stress index, ET is the actual evapotranspiration and PET is the potential evapotranspiration.

Rh was calculated from the soil respiration (Rs) with equation (5), which was proposed by Yu et al. (2010):

\[ \text{Rh} = 0.4679 \times \text{Rs} + 114.42. \]  

Rs was calculated at the monthly scale according to equation (6) (Yu et al. 2010, Chuai et al. 2018):

\[ \text{Rs}_{\text{month}} = (0.588 + 0.118 \times \text{SOC}) \times e^{\ln(1.83 \times e^{-0.66 \times T})} \times \frac{(P + 2.972)}{(P + 5.657)} \times 30. \]  

where SOC is the topsoil (0–20 cm) organic carbon storage density (kg C m\(^{-2}\)), \( T \) is the mean monthly air temperature (°C) and \( P \) is the total monthly precipitation (cm).

2.2.2. Data sources and multiple dataset integration

Multiple datasets were used as inputs to drive the calculation of NEP. All datasets are summarized in table 1. As these datasets are varied in format, spatial and temporal resolution, they must be integrated to feed the needs of model input. We first converted all datasets into raster grids with WGS84/Albers equal area conic projection. Then, they were regrouped and resampled into a 1 km \( \times \) 1 km grid for matching.
Figure 2 is the workflow to describe the procedure of data integration and NEP calculation. Before integration, we filled data gaps due to missing observations in climate stations and bad-quality records in MOD13A1 NDVI time series. For missing observation records in climate stations, we filled the gaps by values of the neighborhood days. For bad-quality records in the MOD13A1 NDVI time series, we masked all cloud and aerosol affected pixels based on the quality indicator layer in the MOD13A1 dataset and filled the gaps with linear interpolation, and smoothed the data using a Savitzky–Golay filter algorithm. Explicit information about the data source and preprocessing is described in appendix S4.

2.2.3. Model evaluation
To improve the feasibility of the simulation results, we compared our estimated NPP and NEP with available NPP and NEP datasets that were already validated in published studies. Available NPP was derived from the MOD17A3H product (https://lpdaac.usgs.gov/products/mod17a3hv006/), and three global NEP datasets based on machine learning methods (Bodesheim et al 2018, Jung et al 2020, Zeng et al 2020). All datasets were masked according to the range of the BTSSCP zone. Notably, the comparison of our data showed a high degree of consistency with these existing datasets, indicating the reliability of our results (appendix S2, figure S1(b)). Meanwhile, our estimated NPP was slightly higher than that of the MOD17A3H product (appendix S2, figure S1(a)). This was mainly due to MOD17 C6 products largely underestimating productivity for most ecosystems (Wang et al 2017, Zhang et al 2017).

2.3. Estimation of the effect of change factors on carbon sinks
2.3.1. Modeling setup procedure
2.3.1.1. Separating the effect of climate and CO₂ on FPAR
Apart from LC/land management (LM), climate change and rising CO₂ also affected FPAR. To separate the net effect of climate change and rising CO₂ on the carbon sink, we must construct FPAR which is only driven by climate change or rising CO₂.

To eliminate the effect of LULC change, we chose patches without LULC change in natural reserves of the BTSSCP zone (figure 1(a)) as samples to construct a random forests regression (RF) model. Explicit information about natural reserves is described in appendix S4. Then we extracted the monthly temperature, precipitation, PET and CO₂ concentration as predictors and FPAR as the explanatory variable of these areas during 2001–2019 to drive the RF model. Consistency in both training and validation was good, indicating the feasibility of our assumption (appendix S4, figure S2). Next, we used the trained RF to estimate the FPAR under the sole effect of climate change factors and rising CO₂ to meet the needs of subsequent analysis.

2.3.1.2. Scenario design
To separate the respective effect of climate change, rising CO₂ and ERPs on the carbon sink, we modeled four scenarios (B, CLIM, CO₂, R) based on different combinations of inputs in land and climate factors (table 2). Here, scenario B was designed to analyze the state and change in the carbon sink under business as usual. Scenario CLIM was used to quantify the effect of climate change on the carbon sink only. Likewise, scenario CO₂ was used to quantify the effect of rising CO₂ on the carbon sink and scenario R was used to quantify the effect of real change on the carbon sink.

2.3.1.3. Scenario comparison to distinguish the respective effects of different factors on the carbon sink
Here, we use equation (7) to assess the effect of the change in individual factors on the carbon sink

\[
CS_k = \sum_{i=2001}^{2019} \text{NEP}_{k,i} - \sum_{i=2001}^{2019} \text{NEP}_{B,i}. \tag{7}
\]

Here \(CS_k\) is the cumulative NEP difference in LULC \(t\) between scenario \(k\) and scenario B on the carbon sink from 2001 to 2019, \(\text{NEP}_{k,i}\) is the NEP under scenario \(k\) of year \(i\) and \(\text{NEP}_{B,i}\) is the NEP under scenario B of year \(i\).

Next, the effect of different factors on the carbon sink was quantified according to table 3. Considering

### Table 1. Required data for NEP evaluation.

| Data          | Spatial resolution | Period       | Time scale | Sources                          |
|---------------|--------------------|--------------|------------|----------------------------------|
| LULC          | 30 m               | 2001–2019    | Yearly     | MCD Yang et al 2021              |
| NDVI          | 500 m              | 2001–2019    | 16 day     | MOD13A1 (MODIS product)          |
| SOC           | 1000 m             | Constant     | Constant   | Harmonized World Soil Database v 1.2 |
| ET/PET        | 1000 m             | 2001–2019    | 8 day      | MOD16A2 (MODIS product)          |
| Temperature   | 1000 m             | 2001–2019    | Monthly    | Chinese National Climate Data Center |
| Precipitation | 1000 m             | 2001–2019    | Monthly    | Chinese National Climate Data Center |
| Radiation     | 1000 m             | 2001–2019    | Monthly    | Chinese National Climate Data Center |

ET, evapotranspiration; LULC, land use/land cover; NDVI, normalized difference vegetation index; PET, potential evapotranspiration; SOC, soil organic carbon.
Table 2. Summary of factorial model simulations.

| Scenarios             | LULC | FPAR  | RAD  | TEM | PRE | WSI |
|-----------------------|------|-------|------|-----|-----|-----|
| Baseline (B)          | No   | No    | No   | No  | No  | No  |
| Climate change (CLIM) | No   | Yes   | Yes  | Yes | Yes | Yes |
| Rising CO₂ (CO₂)      | No   | No    | No   | No  | No  | No  |
| Real state (R)        | No   | No    | No   | No  | No  | No  |

LULC, land use/land cover; FPAR, fraction of APR (absorbed photosynthetically active radiation); RAD, radiation; TEM, temperature; PRE, precipitation; WSI, water stress index. ■, Transient input variable from 2001 to 2019. □, Input variable is fixed at the level in 2001, except for climate factors fixed at the average for 2001–2003 (to reduce the uncertainty of inter-annual climate fluctuations).

a The maximum light-use efficiency $\varepsilon_{\text{max}}$ of different LULCs was varied, changes in LULC changed the maximum light-use efficiency, which affects calculation in equation (2).
b The transient FPAR derived from the RF model corresponding to varying climate-driven factors.
c The transient FPAR derived from the RF model corresponding to varying CO₂ driven factors.

Table 3. Equations to disentangle the effects of different factors on the carbon sink (CS).

| Factors            | Equations                                                                 |
|--------------------|---------------------------------------------------------------------------|
| Climate change     | $CS_{\text{CLIM}} = \Delta\text{NEP}_{\text{CLIM,F}} + \Delta\text{NEP}_{\text{CLIM,G}} + \Delta\text{NEP}_{\text{CLIM,C}} + \Delta\text{NEP}_{\text{CLIM,O}}$ |
| Rising CO₂         | $CS_{\text{CO₂}} = \Delta\text{NEP}_{\text{CO₂,F}} + \Delta\text{NEP}_{\text{CO₂,G}} + \Delta\text{NEP}_{\text{CO₂,C}} + \Delta\text{NEP}_{\text{CO₂,O}}$ |
| ERPs               | $CS_{\text{ERPs}} = (\Delta\text{NEP}_{\text{F}} - \Delta\text{NEP}_{\text{CLIM,F}} - \Delta\text{NEP}_{\text{CO₂,F}}) + (\Delta\text{NEP}_{\text{G}} - \Delta\text{NEP}_{\text{CLIM,G}} - \Delta\text{NEP}_{\text{CO₂,G}})$ |
| Non-ERPs           | $CS_{\text{Non-ERPs}} = \Delta\text{NEP}_{\text{R}} - CS_{\text{CLIM}} - CS_{\text{CO₂}} - CS_{\text{ERPs}}$ |

ERPs, ecological restoration project; F, forest; G, grassland; NEP, net ecosystem productivity; O, others; S, shrubland.

Figure 3. The association between LC/LM and ecological restoration projects (ERPs).

The stringent natural ecosystem restoration and protection measures implemented in the BTSSCP zone (Liu et al 2019), we tentatively assumed that all contributions to the carbon sink in both increased and unchanged forests/grassland were due to ERPs under the condition of excluding the impact of climate change and rising CO₂ (figure 3), and that the other LC/LM-induced carbon sink change was due to measures and practices of non-ERPs (table 3).

3. Results

Approximately 507.18 Tg C was sequestered in the BTSSCP zone from 2001 to 2019 (figure 4), and 56.45% and 24.59% of the total carbon sink was contributed by forest and grassland, respectively (figure 4). Compared with the baseline scenario, climate change alone caused the total NEP to decrease by approximately 78.97 Tg C (figure 4). Climate change made the carbon sink in forests and grassland decline by about 39.55 Tg C and 33.43 Tg C, respectively (figure 6). The negative effect of climate change mainly occurred in the mid and southwest areas (figure 5). In contrast, ERPs contributed approximately 199.88 Tg C to the carbon sink compared with baseline (figure 6; appendix S5, table S2). Meanwhile, rising CO₂ also contributed approximately 107.80 Tg C (figure 6). This made the carbon sink in forests and grassland increase by about 3.85 Tg C and 81.04 Tg C, respectively (figure 6).

ERPs induced a positive carbon sink rate change (CSRC) in unchanged forest and grassland of approximately 42.48 g C m⁻² yr⁻¹ and 9.63 g C m⁻² yr⁻¹, respectively (figure 7).
addition, ERPs induced a positive CSRC of approximately 143.80 ± 10.79 g C m⁻² yr⁻¹ in new forests and approximately 16.07 ± 17.49 g C m⁻² yr⁻¹ in new grassland (figure 7). Likewise, rising CO₂ also induced a positive CSRC in forest and grassland of approximately 4.23 g C m⁻² yr⁻¹ and 17.37 g C m⁻² yr⁻¹, respectively (figure 7). Conversely, climate change induced a negative CSRC in forest and grassland of approximately 27.65 g C m⁻² yr⁻¹ and 6.31 g C m⁻² yr⁻¹, respectively (figure 7).

4. Discussion

For evidence of the credibility of the estimated change in the carbon sink contributed by ERPs, we compared our results with values derived from Lu et al (2018) and Liu et al (2019). The comparison showed that our estimate was similar to theirs in the matched period (2001–2010) (appendix S2, figure S2). This suggests confidence in our approach to separate the contribution of ERPs to the carbon sink. In terms of the average carbon sink rate, forest NEP was the highest (311.26 ± 50.51 g C m⁻² yr⁻¹) across all LULCs (appendix S5, figure S1). This value was also similar to that of a previous study (310 ± 285 g C m⁻² yr⁻¹) by Liu et al (2018) but slightly higher than the figures of Zhao et al (2019) (152.45 ± 181.46 g C m⁻² yr⁻¹), Sun et al (2015) (58 ± 76 g C m⁻² yr⁻¹) and Wang et al (2018) (121 ± 5 g C m⁻² yr⁻¹). This difference may be related to the uncertainty in the different methods used in these studies. The methods
used by Zhao et al. (2019) and Sun et al. (2015) were based on inventory data and did not consider the effect of spatial heterogeneity in forest quality and growth state. Moreover, inconsistent timespans were another important cause of the observed differences. Additionally, the method used by Wang et al. (2018) considered only the carbon sink potential of vegetation without considering that of soil. Indeed, the soil carbon sink is a very important component of the total carbon sink of forests in the BTSSCP zone according to the study of Zeng et al. (2014). For grassland, the estimate of the average NEP
(18.69 ± 24.24 g C m⁻² yr⁻¹) (appendix S5, figure S1) was consistent with that of previous studies by Chen et al (2016) (11.25 g C m⁻² yr⁻¹) and Sui and Zhou (2013) (15.97 g C m⁻² yr⁻¹). This consistency was most likely due to the methods used in these studies, which were all based on approaches derived from remote sensing. For cropland, the average NEP estimate (68.61 ± 40.59 g C m⁻² yr⁻¹) of this study was similar to the values of Lu et al (2009) (65.04 ± 16.87 g C m⁻² yr⁻¹) and Du and Liu (2013) (77.45 ± 32.74 g C m⁻² yr⁻¹). In addition, the sensitivity of the CSRC to rising CO₂ that we measured was also similar to the size calculated from MACC-II, Jena CarboScope and TRENDY datasets (Martínez et al 2019) (appendix S2, figure S3), which suggests that our results are reliable.

The effect of climate change on the carbon sink is negative, and widespread drought was probably the major cause. Based on the drought area ratio of varied drought frequency calculated from the 12-month SPEI (appendix S3, figure S1(a)), drought occurred at least once in approximately 50% of the total area, and droughts happened more than 14 times in approximately 22% of the total area for the period 2001–2019. Previous study in local areas has already found that serious drought restricts the vegetation growth to offset the contribution of restoration (Wu et al 2014). Meanwhile, Zhang et al (2020) found that drought would induce a shift from a carbon sink to a carbon source in the grasslands of Inner Mongolia, China. Notably, the annual cumulative drought area declined after 2012 (appendix S3, figure S1(b)). Continuous increase in precipitation, especially after 2012, may be the main reason for reduction in the occurrence and scale of drought (figure 1(c)). Indeed, reduced drought reversed the negative trend of climate change-induced carbon loss in later years (appendix S5, figure S2). However, improvement in the carbon sink resulting from reduced drought did not thoroughly offset the carbon loss caused by prior drought (appendix S5, figure S2).

On the contrary, the carbon sink contributed by ERPs and rising CO₂ reversed the negative effect caused by climate change (figure 6). Compared with rising CO₂, ERPs can enhance the carbon sink more quickly, especially in forests (figure 7). Moreover, the enhancing effect of ERPs in new forests was stronger than in old forests (figure 7). This was mostly due to the larger stems and roots and higher soil organic matter in old forests, which cause higher respiration (Tang et al 2014, West 2020). Likewise, the response of CSRC to rising CO₂ was varied across different LULCs (figure 7), due to the varied sensitivity of different types of vegetation to rising CO₂.

Of the carbon cycles of all LULCs, that of grassland has changed the most dramatically, changing from the largest carbon source to the second largest carbon sink (figure 7). The average grassland carbon sink rate changed from −3.86 g C m⁻² yr⁻¹ to 58.25 g C m⁻² yr⁻¹ from 2001 to 2019 (appendix S5, figure S1). Meanwhile, over 80% of the increase in the grassland carbon sink was from unchanged grassland (appendix S5, table S1). This is most likely due to prohibition of grazing and enclosure implemented in grassland due to ERPs (Wu et al 2013, Li et al 2019, Liu et al 2019). Prior research has already found that light grazing and enclosure would alter the composition of vegetation species, improve grassland productivity and reduce soil respiration to promote the carbon sink (Deng et al 2017, Yu et al 2019, Lin et al 2021). Another important cause is rising CO₂. Previous results have shown that rising CO₂ is an important cause of improvement in the grassland carbon sink in recent decades (Xu et al 2014, Chang et al 2021, Pastore et al 2021). In addition, the current carbon sink rate of grassland is lower than the estimate of Wang et al (2011) for abandoned grassland (128–130 g C m⁻² yr⁻¹). This indicates that carbon sinks in grassland will still increase in the future.

Unlike grassland, forest always was a carbon sink, and the carbon sink rate of unchanged forests (287.54 g C m⁻² yr⁻¹) was higher than that of increased forests (177.28 ± 77.36 g C m⁻² yr⁻¹) (appendix S3, table S1 and appendix S5, table S1). Increased forests are the result of artificial planting, and their stand age is younger than that of unchanged forests. These artificially planted trees were planted for less than 20 years and had not reached a sufficient age to achieve their peak carbon uptake rate (Mora et al 2018, Chen et al 2020). Thus, the carbon sink rate in increased forests still has the potential to improve in the future.

In addition, the carbon sink rate in cropland also increased considerably in the BTSSCP zone (figure 6). The increase in the cropland carbon sink was primarily related to improved irrigation technology (Zhao et al 2013, Peng et al 2021), optimized fertilization (Lu et al 2009, Zhao et al 2013, Liu et al 2019), long-time wheat–maize rotation (Wang et al 2015, Xue et al 2018) and the implementation of straw return (Lu et al 2009, Liu et al 2019). However, uncertainty still exists about the effectiveness of cropland carbon sequestration, as straw return may increase greenhouse gas emissions (Lu et al 2010). Compared with agricultural measures, ERPs are more effective and much lower uncertainty exists, leading to improvements in the carbon sink in forests and grassland. Although the effects of carbon costs and leakage in ERPs may offset part of the carbon sequestration, a greater amount of sequestered carbon is stably preserved (Liu et al 2019).

The continued acceleration in carbon sink improvement in the BTSSCP zone indicates that long-term ERPs achieve greater carbon sink benefits than short-term ERPs (appendix S5, figure S2).
Although previous studies concluded that an increase in carbon sinks will occur in mid-latitude arid and semiarid regions (Post et al. 2018) such as the BTSSCP, the growth of vegetation is slow in these areas owing to water and heat constraints (Pan et al. 2020). Thus, carbon sink improvement in these areas is slow. As demonstrated in this article, if ERPs continue to be implemented in these areas, there could be rapid and noticeable improvements in the carbon sink over time. Compared with rising CO₂, ERPs can sequester CO₂ more quickly (figure 7). However, previous studies have found that if ERPs continue to be implemented in areas restricted by available water, reforestation may lead to a decline in soil moisture which finally causes disease, wilt or death of vegetation (Jia et al. 2017, Zhao et al. 2021). Thus, local species should be given priority in ERPs owing to their better tolerance to withstand the effect of drought and higher water-use efficiency (Craine et al. 2013, Khoury and Coomes 2020). In addition, the implementation of an ecological water conveyance (EWC) plan may also be helpful. An EWC means diverting water from upstream or other basins to the target area. An EWC was implemented in the Heihe watershed in northwest China where the climate is similar to that in the BTSSCP zone (appendix S4, figure S3). The EWC in the Heihe watershed not only increased water resources and promoted the restoration of ecosystems but also promoted economic development with tourism and agriculture (Zhao et al. 2020). Nevertheless, introducing an ERP requires a long-term strategy and a large capital investment and workforce (Yin et al. 2021). A total investment of USD 8.11 billion was made in stage I of the BTSSCP, and more capital investments were made in stage II (Liu et al. 2019). Thus, it is a challenge to balance investments in economic construction and ERPs.

5. Conclusion

In this study, we succeed in separating the effects of climate change, rising CO₂ and ERPs on carbon sinks by setting different scenarios in the BTSSCP zone. Our results demonstrate the significance of ERPs in promoting the regional carbon sink and mitigating climate change. In addition, the negative impact of climate change on the carbon sink was also successfully reversed by ERPs. Moreover, rising CO₂ gained an additional carbon sink. Currently, global warming-induced climate change has caused a large number of regions to change from carbon sinks to carbon sources and has induced a continuing loss of carbon stocks. Although rising CO₂ may also increase the carbon sink in these areas, it is uncertain and much slower than an ERP. Thus, if positive measures such as afforestation and reforestation were conducted in these areas, it would be possible to prevent these areas from changing into carbon sources. Meanwhile, the intensity and scale of ERPs should be adapted to the regional availability of water resources.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Anderegg W R L et al. 2020 Climate-driven risks to the climate mitigation potential of forests Science 368 eaaaz7005

Bodsheim P, Jung M, Gans F, Mahecha M D and Reichstein M 2018 Upscaled diurnal cycles of land–atmosphere fluxes: a new global half-hourly data product Earth Syst. Sci. Data 10 1327–65

Campbell G S 1977 Introduction to Environmental Biophysics vol 1977 (Berlin: Springer)

Cao J, Tian H, Adamowski J F, Zhang X and Cao Z 2018 Influences of afforestation policies on soil moisture content in China’s arid and semi-arid regions Land Use Policy 75 449–58

Carvalhais N et al 2014 Global covariation of carbon turnover times with climate in terrestrial ecosystems Nature 514 213–7

Chang J et al. 2021 Climate warming from managed grasslands cancels the cooling effect of carbon sinks in sparsely grazed and natural grasslands Nat. Commun. 12 118

Chen A et al. 2020 Spatiotemporal dynamics of ecosystem fires and biomass burning-induced carbon emissions in China over the past two decades Geography and Sustainability 1 47–58

Chen C et al. 2019 China and India lead in greening of the world through land-use management Nat. Sustain. 2 122–9

Chen Y Z, Mu S J, Sun Z G, Gang C C, Li J L, Padarian J, Groisman P, Chen J P and Li S W 2016 Grassland carbon sequestration ability in China: a new perspective from terrestrial aridity zones Rangel. Ecol. Manage. 69 84–94

Chen Z, Yu G and Wang Q 2020 Effects of climate and forest age on the ecosystem carbon exchange of afforestation J. For. Res. 31 365–74

Chirino E, Bonet A, Bellot J and Sánchez J R 2006 Effects of 30-year-old Aleppo pine plantations on runoff, soil erosion, and plant diversity in a semi-arid landscape in south eastern Spain CATENA 65 19–29

Chiu X W et al. 2018 Land degradation monitoring using terrestrial ecosystem carbon sinks/sources and their response to climate change in China Land Degrad. Dev. 29 3489–502

Craine J M, Ocheltree T W, Nippert J B, Towne E G, Skibbe A M, Kembel S W and Fargione J E 2013 Global diversity of drought tolerance and grassland climate-change resilience Nat. Clim. Change 3 63–67
Deng L, Shangguan Z-P, Wu G-L and Chang X-F 2017 Effects of grazing exclusion on carbon sequestration in China's grassland Earth-Sci. Rev. 173 84–95
Du Q and Liu H Z 2013 Seven years of carbon dioxide exchange over a degraded grassland and a cropland with maize ecosystems in a semiarid area of China Agric. Ecosystem. Environ. 173 1–12
Duseenge M, E, Duarte A G and Way D A 2019 Plant carbon metabolism and climate change: elevated CO₂ and temperature impacts on photosynthesis, photoprosperation and respiration New Phytol. 211 32–49
Erbaugh J T, Pradhan N, Adams J, Oldekoop J A, Agrawal A, Brockington D, Pritchard R and Chhatre A 2020 Global forest restoration and the importance of prioritizing local communities Nat. Ecol. Evol. 4 1472–6
Fernández-Martínez M et al 2019 Global trends in carbon sinks and their relationships with CO₂ and temperature Nat. Clim. Change 9 73–79
Friedlingstein P et al 2019 Global carbon budget 2019 Earth Syst. Sci. Data 11 1783–838
Heinrich V H A et al 2021 Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change Nat. Commun. 12 1785
Hu Z, Li S, Guo Q, Niu S, He N, Li L and Yu G 2016 A synthesis of the effect of grazing exclusion on carbon dynamics in grasslands in China Glob. Change Biol. 22 1385–93
IPCC 2019 Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (available at: www.ipcc.ch/srdcl/)
Jia X, Wang Y, Shao M A, Luo Y and Zhang C 2017 Estimating regional losses of soil water due to the conversion of agricultural land to forest in China’s loess plateau Ecologicalology 10 e1851
Jung M et al 2020 Scaling carbon fluxes from eddy covariance sites to globe: synthesis and evaluation of the FLUXCOM approach Biogeosciences 17 1343–65
Khoury S and Coomes D A 2020 Resilience of Spanish forests to recent droughts and climate change Glob. Change Biol. 26 7079–96
Lai L, Huang X J, Yang H, Chui X W, Zhang M, Zhong T Y, Chen Z G, Chen Y, Wang X and Thompson J R 2016 Carbon emissions from land-use change and management in China between 1990 and 2010. Sci. Adv. 2 e1601063
Lal R 2003 Soil erosion and the global carbon budget Environ. Int. 29 437–50
Larjavaara M 2014 The world’s tallest trees grow in thermally similar climates New Phytol. 202 344–9
Laskey R et al 2020 Global ecosystems and fire: multi-model assessment of fire-induced tree-cover and carbon storage reduction Glob. Change Biol. 26 5027–41
Li Y, Fan J and Yu H 2019 Grazing exclusion, a choice between biomass growth and species diversity maintenance in Beijing–Tianjin Sand Source Control Project Sustainability 11 1941
Lin X, Zhao H, Zhang S, Li X, Gao W, Ren Z and Luo M 2021 Effects of animal grazing on vegetation biomass and soil moisture on a typical steppe in Inner Mongolia, China Ecologicalology e2350
Liu B J et al 2019 Greenhouse gas emissions and net carbon sequestration of the Beijing–Tianjin Sand Source Control Project in China J. Clean. Prod. 225 163–72
Liu W W et al 2020 The influence of disturbance and conservation management on the greenhouse gas budgets of China’s forests J. Clean. Prod. 261 121800
Liu X P, Zhang W J, Cao J S, Yang B and Cai Y J 2018 Carbon sequestration of plantation in Beijing–Tianjin sand source areas J. Mount. Sci. 15 2148–58
Lu F et al 2018 Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010 Proc. Natl Acad. Sci. USA 115 4039–44
Lu F, Wang X K, Han B, Ouyang Z Y, Duan X N and Zheng H 2010 Net mitigation potential of straw return to Chinese cropland: estimation with a full greenhouse gas budget model Ecol. Appl. 20 634–47
Lu F, Wang X K, Han B, Ouyang Z Y, Duan X N, Zheng H and Miao H 2009 Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland Glob. Change Biol. 15 281–305
Mitchard E T A 2018 The tropical forest carbon cycle and climate change Nature 559 527–34
Mora F, Jaramillo V J, Bhaskar R, Gavito M, Siddique I, Byrnes J E K and Balvanera P 2020 Climate carbon accumulation in neotropical dry secondary forests: the roles of forest age and tree dominance and diversity Ecosystems 21 536–50
Pan S F et al 2020 Climate extreme versus carbon extreme: responses of terrestrial carbon fluxes to temperature and precipitation J. Geophys. Res. Biogeosci. 125 e2019G005252
Pastore M A, Hobbie S E and Reich P B 2021 Sensitivity of grassland carbon pools to plant diversity, elevated CO₂, and soil nitrogen addition over 19 years Proc. Natl Acad. Sci. USA 118 e2016951118
Paul K I, Polglase P J, Nyakumangama J G and Khanna P K 2002 Change in soil carbon following afforestation Forest Ecol. Manage. 166 1–13
Peng M, Han W, Li C, Li G, Xiao X and Zhang M 2021 Diurnal and seasonal CO₂ exchange and yield of maize cropland under different irrigation treatments in semiarid Inner Mongolia Agric. Water Manage. 255 107041
Peng S, Piao S, Ciais P, Fang J and Wang X 2010 Change in winter snow depth and its impacts on vegetation in China Glob. Change Biol. 16 3004–13
Peñuelas J, Ciais P, Canadell J F, Janssens I A, Fernández-Martínez M, Carnicer J, Obersteiner M, Piao S, Vautard R and Sardans J 2017 Shifting from a fertilization-dominated to a warming-dominated period Nat. Ecol. Evol. 1 1438–45
Post E, Steinman B A and Mann M E 2018 Acceleration of phenological advance and warming with latitude over the past century Sci. Rep. 8 9327
Potter C S, Randerson J T, Field C B, Matson P A, Vitousek P M, Mooney H A and Klooster S A 1993 Terrestrial ecosystem production—a process model-based on global satellite and surface data Glob. Biogeochem. Cycles 7 811–41
Potter C, Klooster S, Myeni R, Genoves V, Tam P N and Kumar V 2003 Continental-scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982–1998 Glob. Planet. Change 39 201–13
Quan Q, Tian S S, Luo Y Q, Zhang P Y, Crowthers W Y, Zhuo B, Chen H Y H, Zhou Q P and Niu S L 2019 Water scaling of ecosystem carbon cycle feedback to climate warming Sci. Adv. 5 eaav1131
Ren W, Banger K, Tao B, Yang J, Huang Y and Tian H 2020 Global pattern and change of cropland soil organic carbon during 1901–2010: Roles of climate, atmospheric chemistry, land use and management Geography and Sustainability 8 59–69
Sa C, Meng F, Liu M, Li C, Wang M, Aditya S and Bao Y 2021 Spatiotemporal variation in snow cover and its effects on grassland phenology on the Mongolian Plateau J. Arid Land 13 332–49
Santos D C, Souza P W M, Nascimento W R, Cardoso G F and Dos Santos J F 2020 Land cover change, landscape degradation, and restoration along a railway line in the Amazon biome, Brazil Land Degrad. Dev. 31 2033–46
Schlör F R et al 2017 Climate change reduces extent of temperate drylands and intensifies drought in deep soils Nat. Commun. 8 14196
Shan N, Shi Z, Yang X, Gao J and Cai D 2015 Spatiotemporal trends of reference evapotranspiration and its driving factors in the Beijing–Tianjin Sand Source Control Project Region, China Agric. For. Meteorol. 200 322–33
Sleeter B M, Marvin D C, Cameron D R, Selmans P C, Westerline A L, Kreitzer J, Daniel C J, Liu J X and Wilson T S 2019 Effects of 21st-century climate, land use, and disturbances on ecosystem carbon balance in California Global Change Biol. 25 3334–53

Stephenson N L et al 2014 Rate of tree carbon accumulation increases continuously with tree size Nature 507 90–93

Sui X H and Zhou G S 2013 Carbon dynamics of temperate grassland ecosystems in China from 1931 to 2007: an analysis with a process-based biogeochemistry model Environ. Earth Sci. 68 521–33

Sun Z Z, Peng S J, Li X R, Gou Z D and Piao S L 2015 Changes in forest biomass over China during the 2000s and implications for management For. Ecol. Manage. 357 76–83

Tang J, Luysaert S, Richardson A D, Kutsch W and Janssens I A 2014 Steeper declines in forest photosynthesis than respiration explain age-driven decreases in forest growth Proc. Natl Acad. Sci. USA 111 8856

Tian C, Yue X, Zhou H, Lei Y, Ma Y and Cao Y 2021 Projections of changes in ecosystem productivity under 1.5 °C and 2 °C global warming Glob. Planet. Change 205 103588

Tong X W et al 2020 Forest management in southern China generates short term extensive carbon sequestration Nat. Commun. 11 129

Walker A P et al 2021 Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2 New Phytolet. 229 2413–45

Wang J, Wang X, Xu M, Feng G, Zhang W, Yang X and Huang S 2015 Contributions of wheat and maize residues to soil organic carbon under long-term rotation in north China Sci. Rep. 5 11409

Wang K B, Hu D F, Deng J, Shangguan Z P and Deng L 2018 Biomass carbon storages and carbon sequestration potentials of the Grain for Green Program-Covered Forests in China Ecol. Evol. 8 7451–61

Wang L C, Zhu H J, Lin A W, Zou L, Qin W M and Du Q Y 2017 Evaluation of the latest MODIS GPP products across multiple biomes using global eddy covariance flux data Remote Sens. 9 418

Wang S P, Wilkes A, Zhang Z C, Chang X F, Lang R, Wang Y F and Niu H S 2011 Management and land use change effects on soil carbon in northern China's grasslands: a synthesis Agric. Ecosyst. Environ. 142 329–40

Wang S et al 2020 Recent global decline of CO2 fertilization effects on vegetation photosynthesis Science 370 1295–300

West P W 2020 Do increasing respiratory costs explain the decline with age of forest growth rate? Forest. Res. 31 693–712

Wieder W R, Cleveland C C, Smith W K and Todd-Brown K 2015 Future productivity and carbon storage limited by terrestrial nutrient availability Nat. Geosci. 8 441–4

Wu Z, Wu J, He B, Liu J, Wang Q, Zhang H and Liu Y 2014 Drought offset ecological restoration program-induced increase in vegetation activity in the Beijing–Tianjin Sand Source Region, China Environ. Sci. Technol. 48 12108–17

Wu Z, Wu J, Liu J, He B, Lei T and Wang Q 2013 Increasing terrestrial vegetation activity of ecological restoration program in the Beijing–Tianjin Sand Source Region of China Ecol. Eng. 52 57–68

Xu X, Sha Z, Li D J, Zhou X H, Sherry R A and Luo Y Q 2015 Plant community structure regulates responses of prairies soil respiration to decadal experimental warming Glob. Change Biol. 21 3846–53

Xu Z, Shimizu H, Ito S, Yagasaki Y, Zou C, Zhou G and Zheng Y 2014 Effects of elevated CO2: warming and precipitation change on plant growth, photosynthesis and peroxidation in dominant species from North China grassland Planta 239 421–35

Xue J-F, Pu C, Zhao X, Wei Y-H, Zhai Y-L, Zhang X-Q, Lal R and Zhang H-L 2018 Changes in soil organic carbon fractions in response to different tillage practices under a wheat–maize double cropping system Land Degrad. Dev. 29 1555–64

Yang J and Huang X 2021 The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019 Earth Syst. Sci. Data 13 3907–25

Yin C, Zhao W, Cherubini F and Pereira P 2021 Integrate ecosystem services into socio-economic development to enhance achievement of sustainable development goals in the post-pandemic era Geography and Sustainability 2 68–73

Yu G R, Zheng Z M, Wang Q F, Fu Y L, Zhaung J, Sun X M and Wang Y S 2010 Spatiotemporal pattern of soil respiration of terrestrial ecosystems in China: the development of a geostatistical model and its simulation Environ. Sci. Technol. 44 6074–80

Yu H, Li Y, Oshunanya S O, Are K S, Geng Y, Saggar S and Liu W 2019 Re-introduction of light grazing reduces soil erosion and soil respiration in a converted grassland on the loess plateau, China Agric. Ecosyst. Environ. 280 43–52

Zeng J Y, Matsunaga T, Tan Z H, Saigusa N, Shirai T, Tang Y H, Peng S S and Fukuda Y 2020 Global terrestrial carbon fluxes of 1999–2019 estimated by upsampling eddy covariance data with a random forest Sci. Data 7 315

Zeng X, Zhang W, Cao J, Liu X, Shen H and Zhao X 2014 Changes in soil organic carbon, nitrogen, phosphorus, and bulk density after afforestation of the 'Beijing–Tianjin sandstorm source control' program in China CATENA 118 186–94

Zhang R, Zhao X Y, Zuo X A, Degen A A, Li Y L, Liu X P, Luo Y Y, Qu H, Liu J, Wang X Q 2020 Drought-induced shift from a carbon sink to a carbon source in the grasslands of Inner Mongolia, China Catena 195 104845

Zhang Y L, Song C H, Zhang K R, Cheng X L, Band I E and Zhang Q F 2014 Effects of land use/land cover and climate changes on terrestrial net primary productivity in the Yangtze River Basin, China, from 2001 to 2010 J. Geophys. Res. Biogeosci. 119 1092–109

Zhang Y, Xiao M M, Wu X C, Zhou S, Zhang G L, Qin Y W and Dong J W 2017 Data descriptor: a global moderate resolution dataset of gross primary production of vegetation for 2000–2016 Sci. Data 4 170165

Zhao M M, Yang J L, Zhao N, Liu Y, Wang Y F, Wilson J P and Yue T X 2019 Estimation of China's forest stand biomass carbon sequestration based on the continuous biomass expansion factor model and seven forest inventories from 1977 to 2013 For. Ecol. Manage. 448 528–34

Zhao M et al 2021 Ecological restoration impact on total terrestrial water storage Nat. Sustain. 4 56–62

Zhao W, Ding J, Wang Y, Jia L, Cao W and Tarolli P 2020 Ecological water conveyance drives human-water system evolution in the Haihe watershed, China Environ. Res. 182 109009

Zhao X, Hu K, Li K, Wang P, Ma Y and Stahr K 2013 Effect of optimal irrigation, different fertilization, and reduced tillage on soil organic carbon storage and crop yields in the North China plain J. Plant Nutr. Soil Sci. 176 89–98

Zhou C W, Fu B J, Yang J L, Ren J, Wang L X, Xin L C, Peng W X, Zhang Q F, Xia S W, Zhang Z L, Yang J, Zhang Y L, Song C H, Zhang K R, Cheng X L, Band I E and Zhang Q F 2014 Effects of land use/land cover and climate changes on terrestrial net primary productivity in the grasslands of Inner Mongolia, China Catena 195 104845

Zhou J et al 2020a Impacts of ecological restoration projects on the ecosystem carbon storage of inland river basin in arid area, China Ecol. Indic. 118 106803

Zhu Q W, Pan Y Z, Yang X Q and Song G B 2007 Comprehensive analysis of the impact of climatic changes on Chinese terrestrial net primary productivity Chin. Sci. Bull. 52 3253–60

Zhu Z et al 2016 Greening of the Earth and its drivers Nat. Clim. Change 6 791–5