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A large carbon sink induced by the implementation of the largest afforestation program on Earth

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Abstract

Background Three-North Afforestation Program (TNAP) in China is the largest ecological restoration project on Earth (ongoing from 1978 to 2050), harboring a huge area of newly planted forests, which provides a wealth of goods and ecosystem services that benefit society at levels ranging from region to East Asia. This project-induced carbon (C) sink has been expected to be large, but its size and location remain uncertain.

Results In this study, we investigated the changes in the C stocks of biomass, soil C and the C accumulation benefited from the ecological effects in the project areas from 1978 to 2017 within the Three-North regions (4.069×10^6 km²), and evaluated its project-induced C sequestration. Using a combination of remote sensing images, field observations and national forest inventory data, we estimated a total ecosystem sink of 47.06 Tg C per year (1 Tg = 10^{12} g) increased by the TNAP implementation. Importantly, we first found that the C sink via the ecological effects of this project could contribute to a high proportion up to 15.94%, indicating a critical role of ecological effects in shaping the distribution of C stocks in the protective forests. This finding suggests that it is necessary to explicitly consider carbon sequestration benefited from the ecological effects when estimating C sink and parameterizing C models of the restoration projects in China and globally.

Conclusions Our results update the estimates of C pools in the world's largest ecological restoration project area, demonstrating that this project has substantially contributed to mitigating the climate change.

Keywords Three-North Afforestation Program, Carbon sequestration, Ecological restoration, Carbon sequestration benefited from the ecological effects

Introduction

Forests have an important role in the global carbon (C) cycle and are valued globally for the ecosystem services they provide to society (Fang et al. 2001; Pan et al. 2011; Meena et al. 2019; Dar and Parthasarathy 2022). International negotiations to limit greenhouse gases require understanding the current and potential roles of forest C emission and sequestration in both nature and projected forests (Liu et al. 2000; Sun et al. 2016; Salunkhe et al. 2018; Meena et al. 2019). However, because of rapid population growth and high demands for forest goods and ecosystem services, the long-term intense use of forests

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has led to large-scale ecosystem degradation globally, resulting in a vast loss of plant biomass and soil C stocks. Such large C loss caused by the disturbance of forest ecosystems is a major factor in regional C budgets, and it is believed to be partly responsible for the large inter-annual variability of the terrestrial part of the C balance. The implementation of the ecological restoration projects is expected to improve C accumulation largely.

The Three-North Afforestation Program (TNAP; Fig. 1) in China is the largest ecological afforestation project (4.069×10^6 km², covering more than 42% of China's land area) on Earth, which was initiated in 1978 in 551 counties across 13 provinces in the Northeast, the North Central and the Northwest of China (Three-North) (the initially scheduled scope), spanning almost all of the country's arid and semiarid areas, and is planned to last until 2050 (Yan et al. 2011; Zhu and Song 2021; Qi et al. 2023). The overall objectives of the 73-year TNAP (1978–2050) are to combat desertification and control dust storms, to control soil and water loss, to protect farmland from wind erosion, and to conserve biodiversity, thus improving the environmental conditions in China's Three-North regions through afforestation to increase forest coverage (Zheng et al. 2016; Zhu and Song 2021; Qi et al. 2023). Considerable efforts have been concentrated

on establishing and preserving this huge national ecological project. For example, in the past 40 years (1978–2017), about 35 billion US dollars (convert Chinese Yuan Renminbi to US dollars based on the exchnage rate of December 2017) were invested into TNAP to construct this “Great Green Wall”. The total forested area, including forests (canopy cover > 30%, minimum area > 400 m²), shrublands (canopy cover > 40%, minimum area > 400 m²), and shelterbelts (length > 20 m) has increased from 220,995 km² in 1978 to 379,046 km² in 2017 (Zhu and Zheng 2019). This restoration project largely reduces soil erosion and desertification, improving environmental quality and biodiversity conservation in the project areas. It provides ecosystem services that benefit society at levels ranging from region to as far as East Asia. Because of these multiple roles, the fate of this project-induced contribution to C sequestration should be a global concern.

The continuous increase in the vegetation cover can prevent C loss from vegetation and soil, and consequently enhance C sinks (Bonan 2008; Ouyang et al. 2014, 2016; Wang et al. 2016; Xu et al. 2017). But the potential in sequestering C originated from these ecological effects of the vegetation has rarely been quantitatively evaluated. Although Lu et al. (2018) found that the contribution of this ecological restoration project to regional and

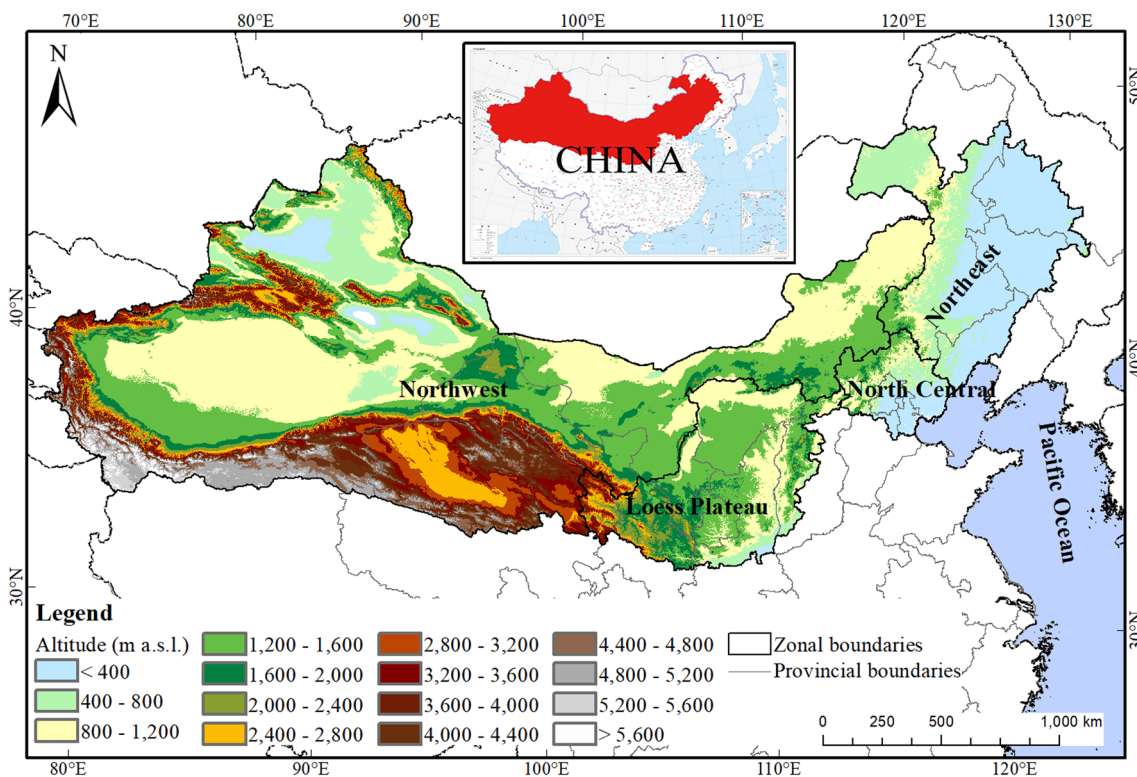


Fig. 1 The spatial location of the TNAP and the four subzones in the Three-North regions (TNR). Three-North means the Northeast, the North Central and the Northwest of China. There are four subzones, i.e., Northeast, North Central, Loess Plateau and Northwest. The initially scheduled scope was 4.069×10^6 km², spanning almost all of the country's arid and semiarid regions, and is planned to last until 2050

national C sequestration is enormous, its size and location largely remain uncertain. In fact, no research has focused on systematically studying C sequestrations of the largest ecological project (TNAP), which limits us to understand the effects of ecological projects on alleviating global climate change. Furthermore, the induced-C sink caused by the ecological effects of this project, which determines its total C sink to a great extent in many protective forests (Zhu and Song 2021), is notoriously excluded in the estimate of the total C pool and the parameterization of C models, blurring the understanding of the functional effects of ecological restoration projects on C sink.

Our study aimed to investigate the changes in biomass carbon stocks, soil carbon levels, and the carbon accumulation resulting from ecological effects in the TNAP areas, while also to evaluate the extent of project-induced carbon sequestration. We hypothesize that the TNAP has significantly increased the biomass carbon stocks, soil carbon levels, and carbon accumulation benefited from ecological effects. We expect the project-induced carbon sequestration to demonstrate a measurable impact on the overall carbon balance within the project areas.

Materials and methods

Study area

China's Three-North regions (TNR) (Northeast, North Central, and Northwest) cover a total area of 4.069×10^6 km² (the initial scheduled scope of TNAP). It is located between 73°26' E and 127°50' E and 33°30' N and 50°12' N, including 551 counties across 13 provinces, and accounts for more than 42.4% of China's total territory (Zhu et al. 2016).

In order to make the assessment accurate and comparable, we selected the initial scheduled scope of TNAP to estimate the carbon stocks although the TNAP scope changed several times after 2001. The TNR is divided into four subzones: Northeast, North Central, Loess Plateau and Northwest according to geo-morphological, climatic characteristics and program objectives (Fig. 1, Additional file 1: Appendix SI) (Bureau of the Three-North Shelter Forest Construction 1993; Zhu and Zheng 2019). The carbon sinks were calculated based on the forest types, tree species, soil types and ecological effects of TNAP in the four subzones, respectively.

Carbon calculation framework and data sources

Carbon calculation framework

The carbon sinks in the TNAP included biomass carbon (BC) of forests, shrublands and shelterbelts, soil carbon (SC), and carbon accumulation benefited from the ecological effects of TNAP implementation (EC). First, we estimated the carbon stocks in 1978 and 2017,

respectively; then, the difference between carbon stocks in 1978 and 2017 was considered as the contribution of TNAP to carbon sinks.

After determining the quantity (area), quality, species and age of forests, shrublands and shelterbelts in the TNAP during 1978 and 2017, the BC (including root biomass) was obtained from 1978 to 2017. Then, the SC stock in 1978 as background (baseline) was estimated at first, and then that in 2017; the difference of SC between 1978 and 2017 was the carbon sink of soils. Finally, EC stocks in 1978 were considered as 0; the EC stocks in 2017 were obtained by estimating the effects of shelterbelts (increased the soil carbon within a certain range from shelterbelts) and soil and water conservation forests (reducing soil loss) on the changes of soil carbon in farmlands and soil erosion areas in TNR, respectively. The data of National Forest Inventories (NFI) plots (Additional file 1: Appendix SII) were used to calibrate the estimations mentioned above.

Data sources

Data sources for estimating the quantity (area), quality, and age of forests, shrublands and shelterbelts, and further for calculating C stocks during 1978 and 2017 include remote sensing images (>2,000 scenes): Landsat MSS images of 1978 (80 m spatial resolution), TM/ETM+ images of 1990, 2000 and 2017 (30 m spatial resolution) and Gaofen-1 in 2017 (10 m spatial resolution) all over the TNR; 9 scenes of SPOT5 and Gaofen-1 (2.5 m spatial resolution) in typical areas (Additional file 1: Appendix SIII). The plot data, 26,508 plots (plot size: 667 m²) of NFI data in China in 2017, were available for the TNR; 20,038 GPS points were from 70 thousand km ground surveys; 1289 field survey plots of forests (plot size: 900 m²) and shrublands (plot size: 400 m²); >300 shelterbelts (with a length of 100 m each shelterbelt). Statistical data encompass historical statistics collected from 1978 to 2017 by local and central governments of China.

Estimation of biomass carbon

The biomass carbon (BC) of forests, shrublands and shelterbelts in TNAP includes the biomass carbon from above-ground and below-ground, but do not include the carbon of understory, dead wood and litter. The BC was estimated by considering the quantity (areas) and quality of forests, shrublands and shelterbelts in TNAP (Additional file 1: Appendix SIII), plus the tree species and afforestation ages (Additional file 1: Appendix SIV). To reduce the errors from geographic differences, the BC was calculated according to the 4 subzones, respectively. The BC was derived by converting from biomass by multiplying a conversion factor of 0.5, because dry biomass is approximately 47–55 percent carbon by weight (Fang

et al. 2001; Pan et al. 2011; Salunkhe et al. 2018; Meena et al. 2019). We estimated the above-ground biomass carbon (ABC) of forests, shrublands and shelterbelts by combination with the data from remote sensing images and survey plots. Then, the below-ground biomass carbon (BBC) was estimated by the ratios between the above-ground and below-ground for main tree species in the TNAP (Fang et al. 1996). The field survey plots and the NFI data were applied to verify the final estimation results. The details for estimation of biomass carbon refer to Additional file 1: Appendix SV.

Estimation of soil carbon

First, the SC stocks of 1978 (baseline) in TNAP areas were estimated from the ground-based soil inventory data from 273 soil profiles collected during 1979–1985 by the Second National Soil Survey (State Soil Survey Service of China 1993; 1994a, b; 1995a, b; 1996). Then, the SC stocks in 2017 were obtained according to 340 soil plots from publications between 2016 and 2018, which were almost overlapped the 273 soil plots. We collected more than 540 articles, including journal papers or dissertations in either English or Chinese conducted in the TNAP areas. Finally, the difference between baseline of SC stocks (1978) and SC stocks after 40 years (2017) was the SC sinks (increment) contributed from the TNAP. The details refer to Additional file 1: Appendix SVI.

Estimation of carbon benefited from ecological effects of TNAP implementation

In TNAP areas, carbon accumulation benefited from the ecological effects (EC) includes two parts: one part is the ecological effects of forests and shrublands on reducing soil loss in the erosion areas, i.e., the carbon in the conserved soils; the other is the ecological effects of shelterbelts on increasing the SC within a certain range from shelterbelts in the farmlands. We ignored the ecological effects of sand fixation forests on preventing wind erosion because the soil carbon in sandy land is much less than those in other soils (Zhu and Zheng 2019). The EC from preventing soil erosion by forests and shrublands was estimated based on Revised Universal Soil Loss Equation (RUSLE) and Lal's results for erosion management and restoration of degraded soils in the TNAP areas (Lal 2004) (Additional file 1: Appendix SVII). The EC from the protected farmlands by shelterbelts was determined by the differences of soil carbon densities between the effective range and the center farmland based on field survey (Additional file 1: Appendix SVIII).

Uncertainty analysis

We conducted uncertainty analysis for carbon estimations of BC and SC according to methods from Wang

et al. (2009, 2011). The uncertainty for calculating C stocks in the TNAP was from forest quantity (area, quality, age, field surveys and models). Uncertainties for BC calculation were estimated on the basis of repeated measurements of sampling plots or the residual (or fitting) errors of models. For the SC uncertainties estimation, the major error sources were up-scaling from field plots to the region.

Results

Biomass carbon sinks in the TNAP

The BC densities in 1978 and 2017 for the forests (above-ground and below-ground C, Mg ha⁻¹) were mapped (Fig. 2). The mean forest BC density increased from 55.80 ± 11.41 Mg ha⁻¹ in 1978 to 76.27 ± 17.90 Mg ha⁻¹ in 2017 (Fig. 2), i.e., the forest C stocks increased from 0.663 ± 0.032 Pg in 1978 to 1.591 ± 0.039 Pg in 2017. The C stocks of shrublands and shelterbelts increased from 0.146 ± 0.016 and 0.034 ± 0.010 Pg in 1978 to 0.429 ± 0.021 and 0.060 ± 0.015 Pg in 2017, respectively. In sum, the biomass C stocks increased from 0.843 ± 0.060 Pg in 1978 to 2.080 ± 0.071 Pg in 2017, i.e., the biomass carbon sequestration increased by 1.237 Pg from 1978 to 2017, and the mean forest BC sink for the past four decades was 30.93 ± 10.74 Tg yr⁻¹ (Table 1).

Soil carbon sinks in the TNAP areas

The SC stocks increased from 5.320 ± 0.593 Pg in 1978 to 5.665 ± 0.617 Pg in 2017 (Table 1). The increment of SC sequestration was 0.345 Pg. The SC sink for the past four decades was 8.63 ± 2.15 Tg yr⁻¹.

Carbon sinks benefited from the ecological effects of TNAP implementation

The areas of soil erosion decreased from 6.72 × 10⁷ ha in 1978 to 2.24 × 10⁷ ha in 2017 in TNAP areas. The mean soil erosion modulus decreased from 5081 Mg km⁻² yr⁻¹ in 1978 to 1190 Mg km⁻² yr⁻¹ in 2017 (Fig. 3). The C sequestration benefited from the conserved soils due to the TNAP implementation was 0.199 ± 0.019 Pg.

The effective range of increasing SC was within 0.5 H (H, mean height of shelterbelts) for 10-year-old shelterbelts, 1.0 H for ~20-year-old shelterbelts (Table 2). The EC benefited from the protection of shelterbelts was 0.101 ± 0.024 Pg in the past 40 years.

The total C sequestration benefited from ecological effects in the TNAP areas was 0.300 Pg, and the EC sink for the past four decades was 7.50 ± 1.59 Tg yr⁻¹.

Carbon sinks in the TNAP

The whole C sinks from the TNAP was derived from biomass growth, soil C increment and C accumulation benefited from ecological effects. In the past four decades, the

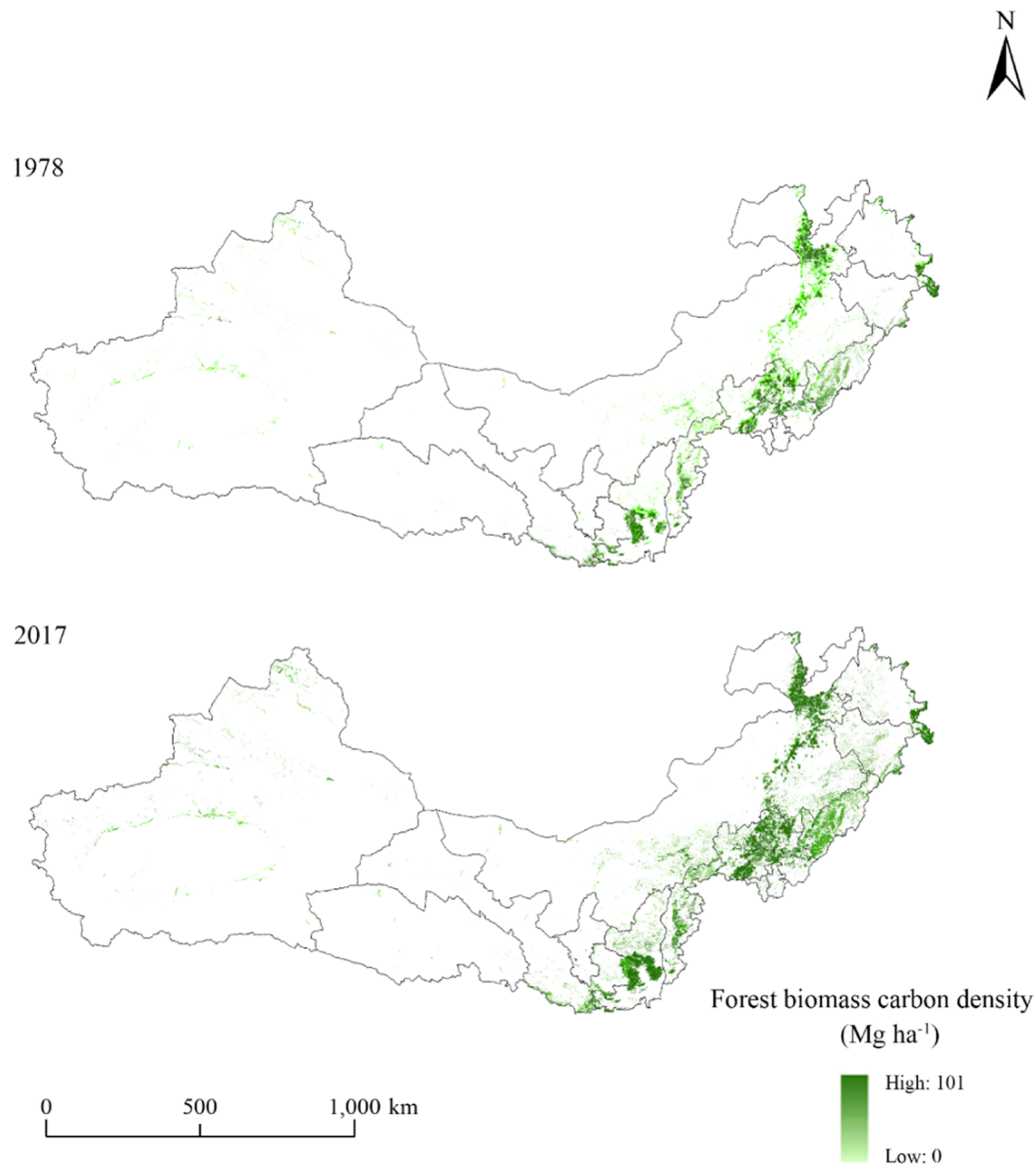


Fig. 2 The distribution of forest biomass carbon density (Mg ha⁻¹) in the TNAP

mean BC, SC and EC were 30.93 ± 10.74 , 8.63 ± 2.15 and 7.50 ± 1.59 Tg yr⁻¹, respectively. The sum C sinks of the TNAP was 47.06 ± 14.48 Tg yr⁻¹ from 1978 to 2017.

Discussion

Here, we first presented bottom-up estimates of C sinks for the TNAP based on the data from recent inventory data, field observations, and remote sensing images, and the integrated analyses from 1978 to 2017. To gain full knowledge of the implicit in estimating C sink induced by the ecological effects of this huge project, we incorporated this effect into the calculation of the total C sink. We focus our assessment on quantifying the dynamics of total ecosystem C accumulation in the project areas from

1978 to 2017. We then provided a standard for assessing the effects of ecological restoration projects on ecosystem C sink. Finally, we propose several management options for the long-term maintenance of the TNAP in China and other ecological restoration projects globally.

Biomass carbon

To validate the reliability of the estimated C stocks of biomass in the TNAP from 1978 to 2017, we compared our results with the previously relevant studies. Fang et al. (2001) reported that total BC stocks (only above-ground biomass, ABC in 1998) of China's forests was 4.75 Pg C, implying that the ABC stocks of the TNAP in 2000 accounted for ~27.58% of the total country forest

Table 1 Carbon sink for the TNAP from 1978 to 2017

Type	Year	Total (Pg)	Carbon sequestration (Pg)	Carbon sink (Tg year ⁻¹)	
Carbon sequestration in biomass	1978	Forests	0.663	1.237	30.93 ± 10.74
		Shrublands	0.146		
		Shelterbelts	0.034		
		Total	0.843		
	2017	Forests	1.591		
		Shrublands	0.429		
Carbon sequestration in soil	1978		5.320	0.345	8.63 ± 2.15
			5.665		
	2017		0.199	0.300	7.50 ± 1.59
			0.101		

BC stocks (Additional file 1: Appendix SIX Table S3). The forest areas in TNAP were 31.53×10^6 ha in 2000 (Zhu and Zheng 2019), accounting for 29.79% of China's forest areas (105.82×10^6 ha in 1998), which indicated that our estimation was highly consistent with previous studies. Furthermore, our estimation (0.843 ± 0.06 Pg C) of total BC (both above-ground and below-ground biomass) stocks for the TNAP in 1978 were about 12.21% to 13.21% of the total BC for China around the 1980s (Liu et al. 2000; Fang et al. 2007; Piao et al. 2009), which indicated that our estimation was closely consistent with these studies as the ratio of ABC to BBC (below-ground biomass carbon) was similar to each other (Additional file 1: Appendix SV Table S1). The mean BC density (55.80 Mg ha^{-1} in 1978) was larger than that (45.75 Mg ha^{-1} in period from 1977 to 1981) by Fang et al. (2001) because the definitions of forests were different, i.e., Fang et al. (2001) defined the forests as a canopy coverage was equal or more than > 20%, which was less than our definition, the canopy coverage was equal or more than > 30%.

Soil carbon

In this study, we estimated the SC sequestered by the TNAP was 345 Tg from 1978 to 2017 ($8.63 \pm 2.15 \text{ Tg yr}^{-1}$), which was within the ranges obtained by Piao et al. (2009) (4.00 ± 4.10 – $39.40 \pm 9.00 \text{ Tg yr}^{-1}$ from 1982 to 1999), which indicated that our estimation was reasonable. Our study indicated that the SC density was $240.73 \text{ Mg ha}^{-1}$ in 1978, which was higher than that obtained by Zhou et al. (2000) (194.6 Mg ha^{-1} , the mean

value from 1989 to 1993). This difference results from the different types of ecosystems monitored, i.e., we monitored only forests and shrublands, but Zhou et al. (2000) included the most of terrestrial ecosystems. The SC in 2017 was $122.78 \text{ Mg ha}^{-1}$ in our study, which was closely similar to that observed by Tang et al. (2018) (106.1 Mg ha^{-1} , the mean value from 2010 to 2015). The comparison mentioned above indicated that our estimation was reliable.

Ecological effect carbon

The EC benefited from the TNAP implementation was 0.30 Pg, including the C in the conserved soils by forests and shrublands, and the increased SC by shelterbelts in the farmlands. The EC in the conserved soils was determined by the reduction of erosion areas and erosion modulus by forests and shrublands. Our previous studies indicated that soil erosion areas and modulus decreased continuously from 1978 to 2008 in TNR (Additional file 1: Appendix SIX Table S4), which was the same as in this study. The EC benefited from shelterbelts was determined by the quantity and age of shelterbelts, which had been validated by our previous studies (Zhu et al. 2016; Zhu and Zheng 2019).

Many previous studies focused on C sequestration in biomass and soil (Persson et al. 2013), considered that the C sequestered in ecological effects is negligible. However, 0.3 Pg is 15.94% of TNAP C sinks within 40 years. This study showed that restored soil has a huge potential for C accumulation in the TNR. The TNAP has been implemented on degraded land that suffered from water

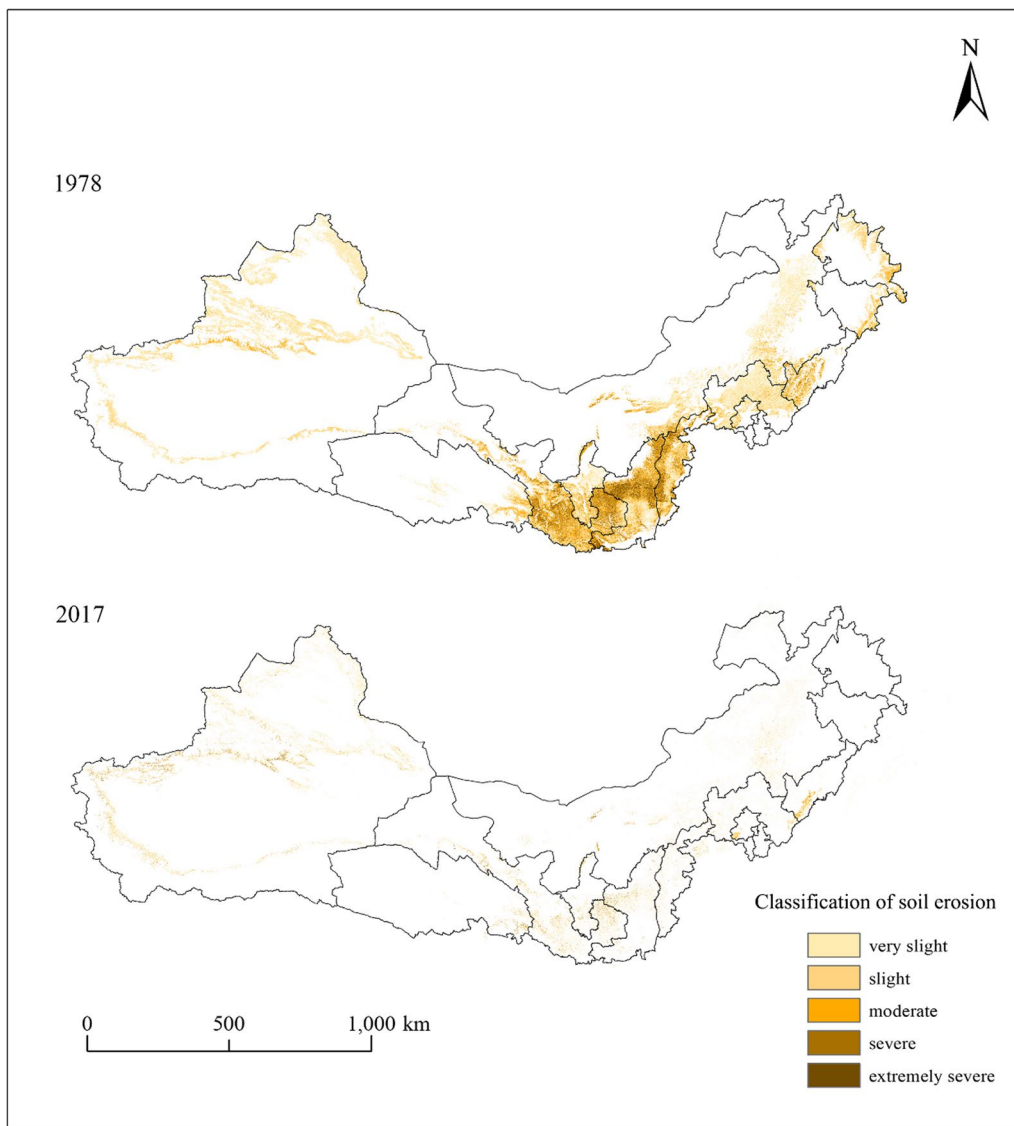


Fig. 3 The changes of soil erosion (erosion modulus) in the TNAP from 1978 to 2017

Table 2 The soil carbon density differences between shelterbelts and farmland

Age	Shelterbelts (kg m^{-2})	0.5 H (kg m^{-2})	1 H (kg m^{-2})	2 H (kg m^{-2})	Farmland center (kg m^{-2})
≤ 10	12.75 ^a	11.97 ^a	10.70 ^b	10.77 ^b	9.54 ^b
10–20	19.10 ^a	19.00 ^a	18.41 ^a	11.11 ^b	10.30 ^b
≥ 20	19.25 ^a	20.59 ^a	18.98 ^a	11.07 ^b	10.60 ^b

H: the height of shelterbelts

*: different letters represent significant differences at $P=0.05$ level (age ≤ 10 : $F=3.76$, $P=0.0187 < 0.05$; age 10–20: $F=3.19$, $P=0.014 < 0.05$; age ≥ 20 : $F=7.09$, $P=0.0083 < 0.05$)

and soil erosion. These lands can sequester C by increasing net primary productivity, which allows for greater C input into soil, which is then retained as soil organic matter (DeGryze et al. 2004; Poeplau and Don 2013).

Uncertainty

The uncertainty of BC is induced by the sampling error, which has been shown to be the largest component of the total error of BC (Phillips et al. 1998). In this study, the coefficient of variation (CV) of the sampling was as high as 20.51%. In the model development, the uncertainty of the MLSR (multiple linear stepwise regression) was 23.90% in the regression error. And the goodness between the measured and estimated BC density by the remaining 20% of the field survey plots for forests was 69.37%. In summary, the uncertainty of BC was around 25%.

In SC estimation, the data sets of SC sequestration after TNAP implementation were combined from field experiments and literature survey. Most sampling sites employed non-retrospective methods, and these methods introduced a great bias into the estimate of SC changes (Hoover 2003). There were no sufficient sampling sites in which the SC was measured before TNAP implementation. Therefore, the uncertainty of soil carbon sequestration cannot be quantified. The uncertainty of EC can be ignored because EC came from soils, which was obtained in experiment.

The uncertainties from spatial and temporal scales can be reduced because BC, SC and EC were estimated in the 4 subzones, Northeast, North Central, Loess Plateau and Northwest, respectively.

Effect of forest health on carbon sink

The overall stability of the project C sink is the net result of contrasting C dynamics in different components and regions associated with natural disturbances and forest management. Despite the consistency of the project C sink since 1978, our analysis revealed important components and regional differences in sink sizes. The maintenance of ecosystem services and/or C sink from the TNAP largely depends on preserving forest health, which is threatened by the speed and amplitude of climate changes projected for these relatively arid and cold regions. Considering the importance of these potential influences the changes may have and the extent over which they may happen in the future, it is imperative that management actions to reduce these threats are available and could be implemented to increase C sinks from biomass, soil and ecological effects. Forest management strategies such as continuous cover silviculture and the enhancement of tree species diversity and landscape

heterogeneity may aid in the maintenance of forest cover, the mitigation of climate change, and the conservation of C sink, water source, and biodiversity. To support critical and timely action on the health of the forests and vegetation, global discussions and forums on sustainable health development and management strategy are needed to place a greater focus on these huge ecological restoration projects.

Conclusions

The world's largest ecological project TNAP had a consistent average sink of 47.06 Tg C yr⁻¹ in the past four decades (1978–2017), which contributed to almost 5% of total industrial carbon dioxide emissions in China between 1978 and 2017. The total forested areas, including forests, shrublands, and shelterbelts increased by 158,051 km² in terms of land cover from 1978 to 2017. The C sinks in above-ground and below-ground biomass increased from 0.843 Pg in 1978 to 2.080 Pg in 2017, which contributed to the largest component sink for this huge project. In contrast, based on the intensive field campaign and publications, there was not a notable sink increase from SC, which increased from 5.320 Pg in 1978 to 5.665 Pg in 2017. Nonetheless, it is important that we found a relatively stable C sink from the ecological effects caused by the implementation of this huge project, which indicated a sink of 7.50 Tg yr⁻¹ between the four decades. Besides the increase of BC and SC sequestrations from this project, its ecological effects such as sheltering farmland and conserving soil probably have a remarkable influence on circumjacent ecosystem function and the fact of C sink. In the project areas, C from ecological effects mainly originate from two parts, one is from its effects on reducing soil loss and maintaining SC in erosion areas; the other is the ecological effects of shelterbelts on reserving SC in a range of incidental farmlands. Our findings provide a benchmark to identify the effectiveness of the national ecological restoration projects on C sink and the ecosystem function assessment.

Abbreviations

ABC	Above-ground biomass carbon
BC	Biomass carbon
BBC	Below-ground biomass carbon
C	Carbon
EC	Carbon benefited from the ecological effects of the TNAP implementation
H	The average height of shelterbelts
MLSR	Multiple linear stepwise regression
NFI	The data of National Forest Inventories
RUSLE	Revised Universal Soil Loss Equation
SC	Soil carbon
TNAP	Three-North Afforestation Program
TNR	The Three-North areas

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13717-023-00455-8>.

Additional file 1: Appendix SI: The basic information of the four subzones (Northeast, North Central, Loess Plateau and Northwest) in the TNAP. **Appendix SII:** The distribution of National Forest Inventories (NFI) plots in the TNAP (Forest plot size: 667 m², 27965 plots; Shrubland plot size: 400 m², 15910 plots). **Appendix SIII:** Methods for estimating the quantity or area and quality of forests, shrublands and shelterbelts in TNAP. **Appendix SIV:** Methods for identifying afforestation ages. **Appendix SV:** Methods for estimating biomass carbon. **Appendix SVI:** Methods for estimating soil carbon. **Appendix SVII:** Methods for estimating the soil erosion modulus and the carbon benefited from ecological effects of preventing soil erosion in TNAP areas. **Appendix SVIII:** Methods for estimating carbon from ecological effects of shelterbelts in TNAP areas. **Appendix SIX:** Our previous results on above-ground biomass carbon and soil erosion areas in TNAP areas.

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Author contributions

JJZ proposed the idea, guided the study and conducted the manuscript writing. YRS carried out field sampling, data collection and wrote the manuscript under the supervision of JJZ. XZ designed methodology and wrote the Supplementary Materials. KY interpreted the results of soil carbon. GGW reviewed and edited the manuscript. CZX carried out data collection and data interpretation. TS helped in the analysis of data and edited the manuscript. JXZ reviewed and edited the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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References

- Bonan GB (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* 320:1444–1449
- Bureau of the Three-North Shelter Forest Construction (1993) Master plan scheme for the Shelter Forest System Program in Three-North Regions of China. Ningxia People's Publishing House, Yinchuan
- Dar AA, Parthasarathy N (2022) Patterns and drivers of tree carbon stocks in Kashmir Himalayan forests: implications for climate change mitigation. *Ecol Process* 11:58
- DeGryze S, Six J, Paustian K, Morris SJ, Paul EA, Merckx R (2004) Soil organic carbon pool changes following land-use conversions. *Glob Chang Biol* 10(7):1120–1132
- Fang JY, Liu GH, Xu HL (1996) Biomass and net production of forest vegetation in China. *Acta Ecol Sin* 16(5):497–508
- Fang JY, Chen AP, Peng CH, Zhao SQ, Ci LJ (2001) Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* 292(5525):2320–2322
- Fang JY, Guo ZD, Piao SL, Chen AP (2007) Terrestrial vegetation carbon sinks in China, 1981–2000. *Sci China Ser D-Earth Sci* 50:1341–1350
- Hoover CM (2003) Soil carbon sequestration and forest management: challenges and opportunities. In: Kimble JM, Heath LS, Birdsey RA, Lal R (eds) The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press, Boca Raton, pp 211–238
- Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* 304(5677):1623–1627
- Liu GH, Fu BJ, Fang JY (2000) Carbon dynamics of Chinese forests and its contribution to global carbon balance. *Acta Ecol Sin* 20(5):733–740
- Lu F, Hu HF, Sun WJ, Zhu JJ, Liu GB, Zhou WM, Zhang QF, Shi PL, Liu XP, Wu X, Zhang L, Wei XH, Dai LM, Zhang KR, Sun YR, Xue S, Huang WJ, Xiong DP, Deng L, Liu BJ, Zhou L, Zhang C, Zheng X, Cao JS, Huang Y, He NP, Zhou GY, Bai YF, Xie ZQ, Tang ZY, Wu BF, Fang JY, Liu GH, Yu GR (2018) Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *Proc Natl Acad Sci USA* 115(16):4039–4044
- Meena A, Bidalia A, Hanief M, Dinakaran J, Rao KS (2019) Assessment of above- and belowground carbon pools in a semi-arid forest ecosystem of Delhi, India. *Ecol Process* 8:8
- Ouyang ZY, Wang Q, Zheng H, Zhang F, Hou P (2014) National ecosystem survey and assessment of China (2000–2010). *Bull Chin Acad Sci* 29(4):462–466
- Ouyang ZY, Zheng H, Xiao Y, Polasky S, Liu JG, Xu WH, Wang Q, Zhang L, Xiao Y, Rao EM, Jiang L, Lu F, Wang XK, Yang GB, Gong SH, Wu BF, Zeng Y, Yang W, Daily GC (2016) Improvements in ecosystem services from investments in natural capital. *Science* 352:1455–1459
- Pan YD, Birdsey RA, Fang JY, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao SL, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. *Science* 333(6045):988–993
- Persson M, Moberg J, Ostwald M, Xu JT (2013) The Chinese Grain for Green Programme: assessing the carbon sequestered via land reform. *J Environ Manage* 126:142–146
- Phillips D, Schroeder P, Brown S, Birdsey R (1998) Land cover dynamics and greenhouse gas emissions: error analysis of large-scale forest carbon budgets. *Institute Cartografic de Catalunya, Barcelona*
- Piao SL, Fang JY, Ciais P, Peylin P, Huang Y, Sitch S, Wang T (2009) The carbon balance of terrestrial ecosystems in China. *Nature* 458(7241):1009–1013
- Poepplau C, Don A (2013) Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. *Geoderma* 192:189–201
- Qi K, Zhu JJ, Zheng X, Wang GG, Li MC (2023) Impacts of the Three-North Afforestation Program (the World's Largest Ecological Restoration Program) on desertification control in sandy land of China. *Gisci Remote Sens* 60(1):2167574
- Salunkhe O, Khare PK, Kumari R, Khan ML (2018) A systematic review on the aboveground biomass and carbon stocks of Indian forest ecosystems. *Ecol Process* 7:17
- State Soil Survey Service of China (1993) China soil series, vol 1. Agricultural Press, Beijing
- State Soil Survey Service of China (1994a) China soil series, vol 2. Agricultural Press, Beijing
- State Soil Survey Service of China (1994b) China soil series, vol 3. Agricultural Press, Beijing
- State Soil Survey Service of China (1995a) China soil series, vol 4. Agricultural Press, Beijing
- State Soil Survey Service of China (1995b) China soil series, vol 5. Agricultural Press, Beijing
- State Soil Survey Service of China (1996) China soil series, vol 6. Agricultural Press, Beijing
- Sun YR, Zhu JJ, Yan QL, Hu ZB, Zheng X (2016) Changes in vegetation carbon stocks between 1978 and 2007 in central Loess Plateau, China. *Environ Earth Sci* 75(4):1–16

- Tang XL, Zhao X, Bai YF, Tang ZY, Wang WT, Zhao YC, Wan HW, Xie ZQ, Shi XZ, Wu BF, Wang GX, Yan JH, Ma KP, Du S, Li SG, Han SJ, Ma YX, Hu HF, He NP, Yang YH, Han WX, He HL, Yu GR, Fang JY, Zhou GY (2018) Carbon pools in China's terrestrial ecosystems: new estimates based on an intensive field survey. *Proc Natl Acad Sci USA* 115(16):4021–4026
- Wang GX, Oyana T, Zhang MZ, Adu-Prah S, Zeng SQ, Lin H, Se JY (2009) Mapping and spatial uncertainty analysis of forest vegetation carbon by combining national forest inventory data and satellite images. *Forest Ecol Manag* 258(7):1275–1283
- Wang GX, Zhang MZ, Gertner GZ, Oyana T, McRoberts RE, Ge HL (2011) Uncertainties of mapping aboveground forest carbon due to plot locations using national forest inventory plot and remotely sensed data. *Scand J Forest Res* 26(4):360–373
- Wang S, Fu BJ, Piao SL, Lü YH, Ciais P, Feng XM, Wang YF (2016) Reduced sediment transport in the Yellow River due to anthropogenic changes. *Nat Geosci* 9:38–41
- Xu WH, Xiao Y, Zhang JJ, Yang W, Zhang L, Hull V, Wang Z, Zheng H, Liu JG, Polasky S, Jiang L, Xiao Y, Shi XW, Rao EM, Lu F, Wang XK, Daily GC, Ouyang ZY (2017) Strengthening protected areas for biodiversity and ecosystem services in China. *Proc Natl Acad Sci USA* 114:1601–1606
- Yan QL, Zhu JJ, Hu ZB, Sun OJ (2011) Environmental impacts of the shelter forests in Horqin sandy land. *Northeast China J Environ Qual* 40(3):815–824
- Zheng X, Zhu JJ, Xing ZF (2016) Assessment of the effects of shelterbelts on the crop yield at regional scale, Northeast China. *Agr Syst* 143:49–60
- Zhou YR, Yu ZL, Zhao SD (2000) Carbon storage and budget of major Chinese forest types. *Chin J Plant Ecol* 24(5):518–522
- Zhu JJ, Zheng X (2019) The prospects of development of the Three-North Afforestation Program (TNAP): on the basis of the results of the 40-year construction general assessment of the TNAP. *Chin J Ecol* 38(5):1600–1610
- Zhu JJ, Song LN (2021) A review of ecological mechanisms for management practices of protective forests. *J Forestry Res* 32(2):435–448
- Zhu JJ, Zheng X, Yan QL (2016) Assessment of impacts of the Three North Protective Forest Program on ecological environments by remote sensing technology. Science Press, Beijing

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