# Postprint: Carbon Sequestration Capacity Estimation for Xinjiang's Terrestrial Ecosystems Based on Natural Climate Solutions

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## Abstract

Natural climate solutions represent a critical strategy for climate change mitigation in the land sector, offering substantial potential for enhancing carbon storage and reducing greenhouse gas emissions. Using a simple empirical model, we quantified the historical carbon sequestration contributions of national ecological restoration projects and active management measures implemented in Xinjiang from 2000 to 2020, and estimated the terrestrial carbon sink and greenhouse gas emission reduction potential of Xinjiang's forest, grassland, and cropland ecosystems from 2020 to 2060 based on 14 natural climate solution pathways. The results indicate that from 2000 to 2020, the average rate of historical contribution from natural climate solutions in Xinjiang was 29.98 Tg CO2e · a-1, with forest restoration being a significant carbon sequestration pathway during this period. From 2020 to 2060, assuming food and fiber security is maintained, the total mitigation potential for the region is 49.53 Tg CO2e · a-1, comprising 10.91 Tg CO2e · a-1 from forest ecosystems, 10.13 Tg CO2e · a-1 from grassland ecosystems, and 28.31 Tg CO2e · a-1 from cropland ecosystems (representing the largest share at 57.35%). Among the 14 future natural climate solution pathways, conservation tillage demonstrates the greatest mitigation potential at 22.72 Tg CO2e · a-1, accounting for 46.06% of the total potential across all pathways. Consequently, appropriate cropland management measures hold considerable promise for carbon sequestration in Xinjiang in the future.

## Full Text

## Preamble

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**Estimation of Carbon Sequestration Capacity in Xinjiang's Terrestrial Ecosystem Based on Natural Climate Solutions**

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## Abstract

Natural climate solutions represent a critical strategy for climate change mitigation in the land sector, offering substantial potential to enhance carbon storage and reduce greenhouse gas emissions. This study employs a straightforward empirical model to quantify the historical carbon sequestration contributions of national ecological restoration projects and proactive management measures implemented in Xinjiang from 2000 to 2020. Based on 14 natural climate solutions pathways, we estimate the terrestrial carbon sink potential and greenhouse gas emission reduction capacity for Xinjiang's forest, grassland, and cropland ecosystems from 2020 to 2060.

The results demonstrate that natural climate solutions in Xinjiang contributed an average mitigation rate of 29.98 Tg $CO_2e \cdot a^{-1}$ between 2000 and 2020, with forest restoration emerging as the dominant carbon sequestration pathway over the past two decades. From 2020 to 2060, while ensuring food and fiber security, the projected mitigation potential across Xinjiang reaches 49.53 Tg $CO_2e \cdot a^{-1}$. Specifically, forest ecosystems contribute 10.91 Tg $CO_2e \cdot a^{-1}$, grassland ecosystems contribute 10.13 Tg $CO_2e \cdot a^{-1}$, and cropland ecosystems represent the largest potential at 28.31 Tg $CO_2e \cdot a^{-1}$, accounting for 57.35% of total mitigation potential. Among the 14 pathways, conservation tillage exhibits the highest mitigation potential at 22.72 Tg $CO_2e \cdot a^{-1}$, comprising 46.06% of all pathways. Therefore, effective cropland management measures hold significant promise for enhancing carbon sequestration in Xinjiang's future.

**Keywords:** natural climate solutions; terrestrial ecosystems; arid regions; carbon sequestration potential; conservation tillage

## 1.1 Study Area Overview

Xinjiang is located in the northwestern border region of China, covering an area of 166$×10^{4}$ km$^2$, approximately 17.3% of China's total land area. The region is characterized by scarce precipitation and abundant sunshine, representing a typical inland arid climate. Xinjiang's topography follows a "three mountains surrounding two basins" pattern, with desert vegetation and Gobi deserts dominating the basins. The region possesses abundant forest resources, with coniferous forests primarily consisting of tall species such as *Picea schrenkiana*, which are widely distributed across Xinjiang's mountainous areas and play a crucial role in maintaining regional ecological balance. Additionally, specialized shrub forests such as *Haloxylon* and *Tamarix* serve vital functions in ecologically fragile zones, positively influencing local ecological equilibrium. Leveraging its extensive grassland resources, Xinjiang has become one of China's important livestock production bases, ranking third nationally in natural grassland area. Cropland resources are predominantly distributed in oasis areas that utilize meltwater from mountain snow and ice along with groundwater irrigation, forming fertile farmland that serves as the foundation of Xinjiang's agricultural development. The protection and management of Xinjiang's forest and grassland resources not only significantly enhance regional environmental quality but also play a critical role in global climate change mitigation strategies. As natural carbon sinks and storage reservoirs, Xinjiang's forests and grasslands are essential in efforts to mitigate climate change worldwide.

## 1.2 Data Sources

Land use data were obtained from the Wuhan University China Land Cover Dataset (CLCD), which encompasses nine land cover categories including cropland, forest, shrubland, grassland, water bodies, ice and snow, barren land, built-up areas, and wetlands, providing annual land cover information at 300 m spatial resolution from 1990 to 2020. Forest area, grassland area, cropland area, and afforestation area data were sourced from the *Xinjiang Statistical Yearbook*, *China Forestry Statistical Yearbook*, and *China Grassland Statistics*. Livestock statistics, crop production data, sown area, and pesticide consumption information were derived from the *Xinjiang Statistical Yearbook*, *China Rural Statistical Yearbook*, and *National Agricultural Product Cost and Benefit Compilation*. Forest fire area data were obtained from the Global Forest Watch website (https://www.globalforestwatch.org/). Atmospheric $CO_2$ concentration time series data were compiled from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) Greenhouse Gas Marine Boundary Layer Reference, with monthly-scale data from 1980 to 2020 based on records from Mauna Loa and Antarctic stations, and data from 2020 to present compiled from NOAA/ESRL records.

## 1.3.1 Calculation Methods for Historical Contributions

This study synthesized multiple ecological restoration projects and management measures implemented in Xinjiang since the 1980s, including the Three-North Shelter Forest Program, Grain-for-Green Project, Natural Forest Protection Program, Returning Grazing Land to Grassland Project, conservation measures, and cover crop measures. These were consolidated into six pathways (forest restoration, natural forest management, grassland restoration, grazing optimization, conservation tillage, and cover crops), with their historical carbon sequestration contributions quantified as the historical contribution of natural climate solutions.

**Forest Restoration:** This pathway primarily calculates the increase in organic carbon sequestration from afforestation in major national ecological restoration projects such as the Three-North Shelter Forest Program (1978–2020) and Grain-for-Green Project (1999–2020). The calculation formula is:

$$HC_1 = \sum(CDI_k \times S_k)$$

where $HC_1$ represents the historical contribution of forest restoration projects (Tg $CO_2$e), $CDI_k$ denotes the carbon density increase in region $k$ (Tg C · $hm^{-2}$), and $S_k$ represents the afforestation area in region $k$ ($10^6$ $hm^2$). The carbon density increase is calculated as:

$$CDI_k = CDB_{2010s} - CDB_{rs} + CDS_{2010s} - CDS_{rs} + (CDIIC_{2010s} - CDIIC_{rs})$$

where $CDB_{2010s}$, $CDS_{2010s}$, and $CDIIC_{2010s}$ represent the average above-ground biomass, soil organic carbon density, and soil inorganic carbon density, respectively, in areas where ecological restoration projects were implemented around 2010. $CDB_{rs}$, $CDS_{rs}$, and $CDIIC_{rs}$ represent the corresponding values in areas without project implementation within the same region. All historical contribution values in this study are converted to Tg $CO_2$e equivalents.

**Natural Forest Management:** This pathway aligns with the carbon sink accumulation from the Natural Forest Resources Protection Project (2000–2020). The calculation formula is:

$$HC_2 = \sum(ARCR_k \times S_k \times t)$$

where $HC_2$ represents the historical contribution of natural forest management projects (Tg $CO_2$e), $ARCR_k$ denotes the carbon sequestration rate increase in region $k$ from reduced natural forest logging (Tg C · $hm^{-2}$ · $a^{-1}$) based on the ninth forest inventory data, $S_k$ represents the natural forest protection area in region $k$ ($10^6$ $hm^2$), and $t$ represents project duration (20 years).

**Grazing Optimization:** This pathway aligns with the carbon sink accumulation from the Returning Grazing Land to Grassland Project (2003–2020). The calculation formula is:

$$HC_3 = \sum(CDI_k \times S_k)$$

where $HC_3$ represents the historical contribution of grazing optimization projects (Tg $CO_2$e), $CDI_k$ denotes the carbon density increase in region $k$ (Tg C · $hm^{-2}$), and $S_k$ represents the grazing optimization area in region $k$ ($10^6$ $hm^2$).

**Grassland Restoration:** This pathway quantifies the carbon sequestration contribution of the Returning Cropland to Grassland Project (2008–2020) to grassland biomass and soil organic carbon. The calculation formula is:

$$HC_4 = \sum (IRSCR_k \times S_k \times t)$$

where $HC_4$ represents the historical contribution of grassland restoration projects (Tg $CO_2$e), $IRSCR_k$ denotes the increase in soil carbon sequestration rate (or reduction in carbon emissions) from grassland restoration in region $k$ (Tg $C \cdot hm^{-2} \cdot a^{-1}$), $S_k$ represents the grassland restoration area ($10^6$ $hm^2$), and $t$ represents project duration (12 years).

**Conservation Tillage:** This pathway primarily calculates the carbon sequestration contribution from no-till practices (2008–2020). The calculation formula is:

$$HC_5 = \sum (CSTG_k \times S_k \times t)$$

where $HC_5$ represents the historical contribution of conservation tillage projects (Tg $CO_2$e), $CSTG_k$ denotes the increase in soil carbon sequestration rate from no-till practices in region $k$ (Tg $C \cdot hm^{-2} \cdot a^{-1}$), $S_k$ represents the area under conservation tillage ($10^6$ $hm^2$), and $t$ represents project duration (12 years).

**Cover Crops:** This pathway calculates the carbon sequestration contribution from cover crops (2008–2020). The calculation formula is:

$$HC_6 = \sum (CCP_k \times S_k \times t \times 50\%)$$

where $HC_6$ represents the historical contribution of cover crop projects (Tg $CO_2$e), $CCP_k$ denotes the additional carbon sequestration rate from cover crops (Tg $C \cdot hm^{-2} \cdot a^{-1}$), $S_k$ represents the cover crop planting area ($10^6$ $hm^2$), and $t$ represents project duration (12 years). The 50% factor assumes that cover crops can be planted during non-growing seasons.

## 1.3.2 Calculation Methods for Climate Mitigation Potential

Based on previous research, this study developed 14 pathways tailored to Xinjiang's arid region conditions, including four forest ecosystem pathways (reforestation, natural forest management, avoided forest conversion, fire management), four cropland ecosystem pathways (conservation tillage, cover crops, nutrient management, rice cultivation management), and six grassland ecosystem pathways (improved forage, animal management, grassland restoration, avoided grassland conversion, legumes in pastures, and grazing optimization). The preliminary calculation method for natural climate solutions' maximum mitigation potential is:

$$M_x = A_{x1} \times F_{x1}$$

where $M_x$ represents the maximum mitigation potential (Tg $CO_2e \cdot a^{-1}$), $A_{x1}$ denotes the maximum implementation level of pathway $x$ in 2060 ($10^6$ $hm^2$), and $F_{x1}$ represents the carbon sequestration rate (Tg $C \cdot hm^{-2} \cdot a^{-1}$). For pathways that avoid carbon emissions, the formula is:

$$M_x = A_{x2} \times F_{x2}$$

where $A_{x2}$ represents the maximum implementation level of pathway $x$ in 2060 ($10^6$ $hm^2$), and $F_{x2}$ denotes the negative impact level (Tg $CO_2e \cdot hm^{-2} \cdot a^{-1}$). The total mitigation potential is calculated as:

$$M_x = M_{x1} + M_{x2}$$

where $M_{x1}$ represents additional carbon sequestration (Tg $CO_2e \cdot a^{-1}$), and $M_{x2}$ represents avoidable carbon emissions (Tg $CO_2e \cdot a^{-1}$). Fire management, nutrient management, improved forage, animal management, and grazing optimization use formula (2), while the remaining nine pathways use formula (1).

## 2 Results and Analysis

### 2.1 Historical Contributions of Natural Climate Solutions

Between 2000 and 2020, natural climate solutions practices in Xinjiang cumulatively contributed 599.66 Tg $CO_2e$, with the 14 pathways delivering an average historical contribution rate of 29.98 Tg $CO_2e \cdot a^{-1}$, offsetting 3.8% of the average annual emissions during the same period (790 Tg $CO_2e \cdot a^{-1}$). Forest restoration emerged as the primary contributor to historical mitigation capacity, accounting for 344.35 Tg $CO_2e$ (57.43% of all pathways). Additionally, natural forest management provided substantial climate mitigation opportunities, with a cumulative historical mitigation capacity of 145.50 Tg $CO_2e$ (24.26% of all pathways). Grazing optimization, cover crops, conservation tillage, and grassland restoration contributed smaller amounts of 86.39 Tg $CO_2e$, 15.86 Tg $CO_2e$, 6.59 Tg $CO_2e$, and 1.07 Tg $CO_2e$, respectively.

From an ecosystem perspective, pathways related to forest ecosystems exhibited the highest historical mitigation capacity at 489.86 Tg $CO_2e$ (81.69% of all pathways). Grassland ecosystem-related pathways contributed 86.39 Tg $CO_2e$ (14.41% of all pathways), with grazing optimization accounting for 98.77% of grassland pathway contributions. Cropland ecosystem-related pathways contributed 23.41 Tg $CO_2e$ (3.90% of all pathways), with cover crops contributing 67.76% of cropland pathway contributions.

### 2.2 Future Climate Mitigation Potential of Natural Climate Solutions

Based on effective ecological restoration projects and management measures implemented in China in recent years, as well as the adaptation action strategy outlined in "Achievements, New Goals, and New Measures of Nationally Determined Contributions" and the "Overall Plan for Major National Projects on Protection and Restoration of Important Ecosystems (2021–2035)," this study analyzed and projected the maximum additional mitigation potential of 14 natural climate solutions pathways for Xinjiang's arid region under food and fiber security constraints. The 14 pathways could provide up to 49.53 Tg $CO_2e \cdot a^{-1}$ of mitigation potential for Xinjiang from 2020 to 2060. Among these, nine pathways increase carbon sinks (reforestation, grassland restoration, legumes in pastures, conservation tillage, nutrient management), while the remaining five pathways reduce greenhouse gas emissions.

**2.2.1 Forest Ecosystem** The climate mitigation potential of different forest ecosystem pathways is illustrated in Figure 1 [Figure 1: see original paper]. The maximum mitigation potential of the four forest ecosystem pathways will reach 10.91 Tg $CO_2e \cdot a^{-1}$, accounting for 22.12% of the total mitigation potential across all 14 pathways. Considering climatic conditions, water resource pressure, cropland protection policies, and urbanization constraints, the maximum new afforestation area in Xinjiang after 2020 is projected to be $92\times10^{4}$ $hm^2$. Reforestation shows the highest potential at 6.97 Tg $CO_2e \cdot a^{-1}$, comprising 63.85% of forest ecosystem mitigation potential. The relatively small reforestation potential reflects constraints on annual afforestation rates. Natural forest management, as the second-largest mitigation pathway for forest ecosystems, has a maximum mitigation potential of 3.93 Tg $CO_2e \cdot a^{-1}$ from 2020 to 2060, accounting for 36.03% of forest ecosystem mitigation potential. Since 2000, Chinese law has prohibited harvesting natural forests for fuelwood and timber, allowing protected natural forests to transition from young and middle-aged stands to near-mature and mature stands with enhanced carbon sequestration capacity. Fire management shows a maximum mitigation potential of $1.09\times10^{-1}$ Tg $CO_2e \cdot a^{-1}$ from 2020 to 2060, with wildfire areas substantially reduced through fire control, preventive measures, and regular fire management since 2000. The risk of forest conversion to other land uses is relatively small, with a maximum mitigation potential of $2.79\times10^{-2}$ Tg $CO_2e \cdot a^{-1}$ from 2020 to 2060.

**2.2.2 Cropland Ecosystem** Cropland ecosystems demonstrate significant advantages in future climate change mitigation, with a total maximum mitigation potential of 28.31 Tg $CO_2e \cdot a^{-1}$ across four pathways. Conservation tillage originated in ecologically fragile regions, focusing on reducing soil disturbance through minimal tillage, no-till, and straw return to decrease soil erosion and protect the environment. Since 2000, China has promoted conservation tillage, which shows remarkable advantages for Xinjiang's future climate mitigation with a maximum potential of 22.72 Tg $CO_2e \cdot a^{-1}$, accounting for 80.30%

of cropland ecosystem mitigation potential. Cover crops, as the second-largest contributor in cropland ecosystems, will reach a maximum mitigation potential of 4.82 Tg $CO_2e \cdot a^{-1}$, comprising 17.02% of cropland ecosystem mitigation potential. Nutrient management and rice cultivation management have maximum mitigation potentials of 0.76 Tg $CO_2e \cdot a^{-1}$ and 0.11 Tg $CO_2e \cdot a^{-1}$, respectively, with rice cultivation management limited by Xinjiang's natural climate conditions and small planting area.

**2.2.3 Grassland Ecosystem** The maximum total mitigation potential of the six grassland ecosystem pathways is projected to be 10.13 Tg $CO_2e \cdot a^{-1}$ (20.53% of total potential). Xinjiang's developed livestock industry makes improved forage the largest contributor among grassland pathways, with a maximum mitigation potential of 4.82 Tg $CO_2e \cdot a^{-1}$, accounting for 69.70% of grassland ecosystem mitigation potential. Animal management pathways reduce $CH_4$ emissions through improved animal reproductive performance and health, with a maximum mitigation potential of $2.79\times10^{-1}$ Tg $CO_2e \cdot a^{-1}$. Limited by future grassland restoration area constraints, grassland restoration pathways have a maximum mitigation potential of 1.07 Tg $CO_2e \cdot a^{-1}$, comprising 10.55% of grassland ecosystem mitigation potential. Cropland expansion and overgrazing are primary causes of grassland conversion in Xinjiang, and avoided grassland conversion pathways offer a new mitigation opportunity of 1.78 Tg $CO_2e \cdot a^{-1}$, accounting for 17.53% of grassland ecosystem mitigation potential. Grazing optimization can be applied to smaller areas with a maximum mitigation potential of $6.23\times10^{-2}$ Tg $CO_2e \cdot a^{-1}$. Additionally, legumes in pastures show a maximum mitigation potential of $2.40\times10^{-1}$ Tg $CO_2e \cdot a^{-1}$.

### 2.3 Spatial Comparison of Natural Climate Solutions Mitigation Potential

The climate mitigation potential of the 14 natural climate solutions pathways in Xinjiang from 2020 to 2060 shows substantial spatial variation across prefectures. The mitigation potential of forest ecosystem natural climate solutions follows a spatial pattern of higher potential in southern Xinjiang than northern Xinjiang. For cropland ecosystem natural climate solutions, the highest mitigation potentials occur in the directly-administered counties and cities of Ili Kazakh Autonomous Prefecture and Kashgar Prefecture, reaching 5.49 Tg $CO_2e \cdot a^{-1}$ and 3.24 Tg $CO_2e \cdot a^{-1}$, respectively. The mitigation potential of grassland ecosystem natural climate solutions is highest in Ili Kazakh Autonomous Prefecture and Kashgar Prefecture, at 5.66 Tg $CO_2e \cdot a^{-1}$ and 4.45 Tg $CO_2e \cdot a^{-1}$, respectively. Conservation tillage, improved forage, and reforestation emerge as the three pathways with the greatest contribution, with conservation tillage alone accounting for 46.06% of total mitigation potential across all 14 pathways, while improved forage and reforestation contribute 14.31% and 14.12%, respectively. For most prefectures, conservation tillage represents the largest mitigation pathway, whereas reforestation is the primary pathway for Bayingolin Mongol Autonomous Prefecture, and improved forage is the largest pathway for Kizilsu Kirghiz Autonomous Prefecture. Notably, natural forest management constitutes a significant pathway for Karamay, Hami, Changji Hui Autonomous Prefecture, and Bayingolin Mongol Autonomous Prefecture, with contribution rates ranking among the top three pathways. Due to limited land area, Turpan, Karamay, Hami, and Urumqi have restricted scope for implementing natural climate solutions and consequently show lower climate mitigation potential contributions.

Figure 2 [Figure 2: see original paper] illustrates the spatial distribution of mitigation potential for natural climate solutions from 2020 to 2060.

## 3 Discussion

China's carbon emissions accounted for 30.7% of global emissions in 2020, with Xinjiang's recent emissions reaching 215 Tg. Our results indicate that Xinjiang's 14 natural climate solutions pathways could provide up to 49.53 Tg $CO_2e \cdot a^{-1}$ of mitigation potential from 2020 to 2060, offsetting approximately 23% of annual carbon emissions. This mitigation potential can make significant contributions toward achieving the "dual carbon" goals alongside industrial emission reductions and energy transitions, while also providing environmental and social benefits including biodiversity protection and water quality improvement. Unlike previous studies, this research reveals that cropland ecosystems account for the largest proportion of mitigation potential (57.35%), followed by forest ecosystems (22.12%) and grassland ecosystems (20.53%). This primarily reflects saturation effects in forest restoration and natural forest management, whereas cropland ecosystems can provide continuous mitigation benefits. Effective farmland management thus emerges as a crucial measure for enhancing climate mitigation capacity.

Conservation tillage originated in ecologically fragile regions, focusing on reducing soil disturbance through minimal tillage, no-till, and straw return to decrease soil erosion and protect the environment. No-till agriculture avoids soil inversion, preserving soil structure and reducing organic matter decomposition and oxidation, thereby preventing $CO_2$ release. Crop residue cover and deep root growth prevent soil erosion, enhance water retention, and promote microbial activity beneficial for carbon fixation. This study demonstrates that conservation tillage alone accounts for 46.06% of total mitigation potential across all 14 pathways, representing an effective cropland management practice for significant carbon sequestration. Previous natural climate solutions research often overlooked this pathway due to uncertainty regarding its net carbon sink effects and impacts on grain yield. Benefiting from Xinjiang's vast grasslands and developed livestock industry, improved forage becomes the second-largest opportunity after conservation tillage, potentially reaching 4.82 Tg $CO_2e \cdot a^{-1}$. Reforestation ranks third in climate change mitigation potential by increasing forest coverage, enhancing carbon storage, and promoting biodiversity, with a potential of 6.97 Tg $CO_2e \cdot a^{-1}$. These measures can all provide substantial mitigation contributions for Xinjiang.

Although this study updates mitigation potential estimates for natural climate solutions by integrating recent research, several uncertainties remain. First, trade-offs may exist among pathways across different ecosystems, which were not accurately quantified in future mitigation potential calculations. Second, beyond climate mitigation, natural climate solutions offer numerous co-benefits including biodiversity improvement, air purification, soil enrichment, and water source protection, whose carbon sequestration benefits are not reflected in this study.

## 4 Conclusions

This study estimates Xinjiang's historical carbon sequestration contributions and future mitigation potential based on national ecological restoration projects and 14 natural climate solutions pathways, revealing the critical role of cropland ecosystems in climate change mitigation. Key conclusions are:

1) Ecological protection and restoration projects implemented in Xinjiang from 2000 to 2020 cumulatively contributed 599.66 Tg $CO_2e$, with an average rate of 29.98 Tg $CO_2e \cdot a^{-1}$. Forest ecosystems exhibited the highest historical mitigation capacity, with forest restoration serving as Xinjiang's important carbon sequestration pathway over the past two decades.

2) From 2020 to 2060, Xinjiang's maximum mitigation potential is approximately 49.53 Tg $CO_2e \cdot a^{-1}$, offsetting about 23% of carbon emissions. Cropland ecosystems show the largest mitigation potential at 28.31 Tg $CO_2e \cdot a^{-1}$ (57.35% of total), followed by forest ecosystems at 10.91 Tg $CO_2e \cdot a^{-1}$ and grassland ecosystems at 10.13 Tg $CO_2e \cdot a^{-1}$. Conservation tillage, improved forage, and reforestation emerge as the three pathways with greatest mitigation potential. The dominant role of cropland ecosystem mitigation potential demonstrates that effective cropland management measures can generate significant climate mitigation benefits.

3) Spatially, the directly-administered counties and cities of Ili Kazakh Autonomous Prefecture, Kashgar Prefecture, Aksu Prefecture, and Changji Hui Autonomous Prefecture will become the four regions with highest climate mitigation potential. Due to limited land area, Turpan, Karamay, Hami, and Urumqi show lower climate mitigation potential.

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*Note: Figure translations are in progress. See original paper for figures.*