



# Biophysical and economic constraints on China's natural climate solutions

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**Natural climate solutions (NCS) are strategies for climate mitigation in the land sector that increase carbon storage or avoid GHG emissions. Here we estimate China's historic NCS mitigation at 0.6 (0.5–0.7) PgCO<sub>2</sub>e yr<sup>-1</sup> (95% CI) during 2000–2020 (8% of fossil CO<sub>2</sub> emissions in the contemporary period). Through new NCS activities, the future maximum potential for NCS is projected at 0.6 (0.3–1.0) PgCO<sub>2</sub>e yr<sup>-1</sup> (6% of fossil CO<sub>2</sub> emissions) during 2020–2030 and 1.0 (0.6–1.4) PgCO<sub>2</sub>e yr<sup>-1</sup> during 2020–2060. Of the future NCS potentials, 26–31%, 62–65% and 90–91% can be achieved at mitigation costs of US\$10, US\$50 and US\$100 (MgCO<sub>2</sub>e)<sup>-1</sup>, respectively. Thus, NCS can contribute substantially to China's Nationally Determined Contributions over the next 10 to 40 years but require a national strategy to reach climate goals and ensure co-benefits for people and nature.**

Natural climate solutions (NCS), a suite of land-management options including protecting, restoring and sustainably managing ecosystems<sup>1</sup>, provide readily implementable approaches to sequester carbon in terrestrial pools and/or reduce GHG emissions<sup>2</sup>. NCS are a complement to, not a substitute for, emissions reductions related to decreased use of fossil fuels and decarbonization of energy and transportation sectors. They are expected to slow the rate of global warming in the next 10–40 years, in parallel with the development of mitigation technologies and energy transformation<sup>3</sup>.

Following the first submission in 2015, China submitted its updated Nationally Determined Contributions (NDCs) in 2021. This included a 'net-zero' commitment, with a peak in CO<sub>2</sub> emissions before 2030 and net carbon neutrality being achieved by 2060<sup>4</sup>. Over the past decades (especially since 1999), China has strengthened its efforts in ecological restoration and protection<sup>5</sup>. While not all the projects were originally designed for carbon sequestration and climate change mitigation, collectively they made a substantial contribution to China's terrestrial ecosystem carbon sink<sup>6–8</sup>. Some adaptive action strategies such as China's Achievements, New Goals and New Measures for Nationally Determined Contributions<sup>9</sup> and Master Plan of Major Projects of National Important Ecosystem Protection and Restoration (2021–2035)<sup>5</sup> have been released, proposing a series of strategies for ecosystem management in the next decades to support implementation of the NDCs. So far, the contributions to emissions reductions from recent projects equivalent to NCS activities have not been fully quantified. More important, the mitigation potential of future NCS activities and their contribution to China's climate goals is largely unknown<sup>2</sup>.

In this Article, we quantified 16 distinct pathways (see definitions and descriptions in Supplementary Tables 1 and 2) to provide an integrated evaluation of the climate mitigation capacity of previous projects during 2000–2020 and the future NCS potentials

during 2020–2030 and 2020–2060 by conserving, restoring and improving management of forests, croplands, grasslands and wetlands in China. The evaluation of the mitigation capacity of previous projects for 2000–2020 is a foundation to understand the historical contribution and a baseline for setting feasible boundaries for future additional NCS pathway projections (Supplementary Tables 1 and 2). We first provide estimates of the historical mitigation capacity of projects during 2000–2020, as well as the future 'maximum additional mitigation potential' (MAMP) of NCS by additional stewardship options under biophysical constraints in the next 10 (by 2030) and 40 (by 2060) years, measured in CO<sub>2</sub> equivalents per year (CO<sub>2</sub>e yr<sup>-1</sup>). We then constrain NCS levels by mitigation cost thresholds. We note that the essence of NCS is to seek new opportunities and approaches with additionality over the baseline (2000–2020 in this study).

## Overall NCS potential

During 2000–2020, the total mitigation capacity of the nine pathways related to previous projects was 0.6 (0.5–0.7) PgCO<sub>2</sub>e yr<sup>-1</sup> (95% confidence interval (CI)) (Fig. 1a), counterbalancing 8% of the mean annual fossil CO<sub>2</sub> emissions in the same period (7.5 PgCO<sub>2</sub> yr<sup>-1</sup>), in which the increased carbon sequestration from ecosystems (0.5 PgCO<sub>2</sub> yr<sup>-1</sup>, excluding CH<sub>4</sub> and N<sub>2</sub>O) is about 54% (28–80%) of the overall land carbon sink in China (0.18–0.51 PgC yr<sup>-1</sup>) (ref. 10). During 2020–2030, the maximum potential of NCS (MAMP) of the 16 pathways is projected at 0.6 (0.3–1.0) PgCO<sub>2</sub>e yr<sup>-1</sup> (Fig. 1b), which is 6% of the mean annual CO<sub>2</sub> emissions during the same period (assuming the industrial CO<sub>2</sub> emissions at year 2030 to be around 10–12 PgCO<sub>2</sub> yr<sup>-1</sup>) (ref. 11). The MAMP is projected at 1.0 (0.6–1.4) PgCO<sub>2</sub>e yr<sup>-1</sup> during 2020–2060 (Fig. 1c).

The realization and importance of diverse NCS pathways comprehensively reflects a nation or region's stewardship of certain ecosystems, land-cover history, status of the ecosystems, land

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ownership, human intervention, technological progress and governance<sup>12</sup>. In the context of China, the land area that can be used for restoration (for example, reforestation, grassland and wetland restoration) (Extended Data Figs. 1 and 2), the technology and land practices that can be applied (for example, water and nutrient management in croplands and grazing management in rangelands) and the land-transfer risk control (for example, avoiding loss of natural land cover to cropland or building) are the direct determinants of ecosystem restoration, management and protection, respectively<sup>1,13</sup>.

### NCS potential by pathway

Historical and future fluxes of individual pathways have contributed to the overall estimates presented in the preceding (Fig. 1a–c and Supplementary Tables 1–3).

### Forest ecosystems

Forest pathways are most important for the historical mitigation capacity and future potential in China (Fig. 1a–c and Supplementary Table 3). During 2000–2020, the carbon sink in managed forests (including reforestation, natural forest management and fire management) was estimated to be 446 TgCO<sub>2</sub>yr<sup>-1</sup>, contributing 73% of the total flux of the nine NCS pathways (Fig. 1a). Of this total, more than 55% was contributed by reforestation (247 TgCO<sub>2</sub>yr<sup>-1</sup> on an area of 44.7 Mha) and 42% by natural forest management (restricted timber logging) (189 TgCO<sub>2</sub>yr<sup>-1</sup> on an area of 41.3 Mha). Fire management made a small contribution of 3% (10 TgCO<sub>2</sub>yr<sup>-1</sup>), in which 9 TgCO<sub>2</sub>yr<sup>-1</sup> was contributed by fire prevention and 1 TgCO<sub>2</sub>yr<sup>-1</sup> by prescribed fire.

In the future, the total MAMP from the five forest pathways (including two new pathways) would be 436 TgCO<sub>2</sub>yr<sup>-1</sup> by 2030 and 627 TgCO<sub>2</sub>yr<sup>-1</sup> by 2060, representing 64–68% of the total NCS of the 16 pathways (Fig. 1b,c and scenario setting in Supplementary Table 2). Considering the constraints of water stress, the farmland red line (the minimum acceptable arable land area in China), urbanization and the 26% forest coverage goal by 2035 (similar to the historical value in 1700)<sup>14,15</sup>, the maximum additional area for future reforestation after 2020 will be limited to be 31.8 Mha (Extended Data Figs. 2 and 3), similar to the estimate in ref.<sup>16</sup>, and the MAMP would be 77 TgCO<sub>2</sub>yr<sup>-1</sup> and 235 TgCO<sub>2</sub>yr<sup>-1</sup> by 2030 and 2060, respectively (assuming that 21.7 Mha be reforested by 2030 and 31.8 Mha by 2060). The lower NCS potential of reforestation during 2020–2030 compared with the historical capacity in 2000–2020 is due to the lower carbon flux rate in the 10 yr forest and the smaller reforested area. The magnitude of CO<sub>2</sub> sequestration during 2020–2060 is comparable to the historical value, with the forests getting older (Fig. 1a–c and Supplementary Tables 2 and 3). The MAMP of natural forest management would be almost double (336 TgCO<sub>2</sub>yr<sup>-1</sup>) within the next 40 years because a larger area of natural forests (79.1 Mha) will be restricted from logging (clearcutting of natural forests for fuelwood and timber is prohibited by law in China since 2020), although the carbon sequestration rate of these unlogged forests would slightly decrease as they would shift from younger (mean age 43 years in 2010) to older (mean age 63–93 years in 2030–2060) age classes with a lower uptake rate (Extended Data Fig. 4)<sup>17</sup>. Natural forest management would account for 77% of the total NCS of forest pathways by 2030 and 54% by 2060, when reforestation will have a higher NCS potential (37%) compared with the historical period. Only 5–9% of the total CO<sub>2</sub> flux resides in improved plantations, avoided forest conversion and fire management. Improved plantations by reducing harvest and improving wood residue treatments could contribute a net sink of 17 and 49 TgCO<sub>2</sub>yr<sup>-1</sup> by 2030 and 2060, respectively (Fig. 1b,c). The risk of forest conversion to other land uses would be relatively small (0.01 Mha yr<sup>-1</sup>). Reducing conversion from forest to cultivated or developed land will contribute 6 and 7 TgCO<sub>2</sub>yr<sup>-1</sup> of emissions reduction by 2030 and 2060, respectively. The mean annual

burnt area due to wildfire was greatly reduced (from 0.89 Mha yr<sup>-1</sup> during 1949–1999 to 0.12 Mha yr<sup>-1</sup> during 2000–2017) (Extended Data Fig. 5) since the implementation of a fire-prevention policy in 1987<sup>18</sup>, and future wildfires may also be maintained at a low level (<1 TgCO<sub>2</sub>yr<sup>-1</sup>).

Forest volume is estimated to increase by 8.26 billion m<sup>3</sup> (equivalent to 7.34 PgCO<sub>2</sub> of carbon sequestration) by 2030 over the 2000 level due to reforestation and natural forest management according to our projections, indicating that achieving the goal specified in China's NDCs (6.0 billion m<sup>3</sup> over the 2005 level)<sup>4</sup> is achievable.

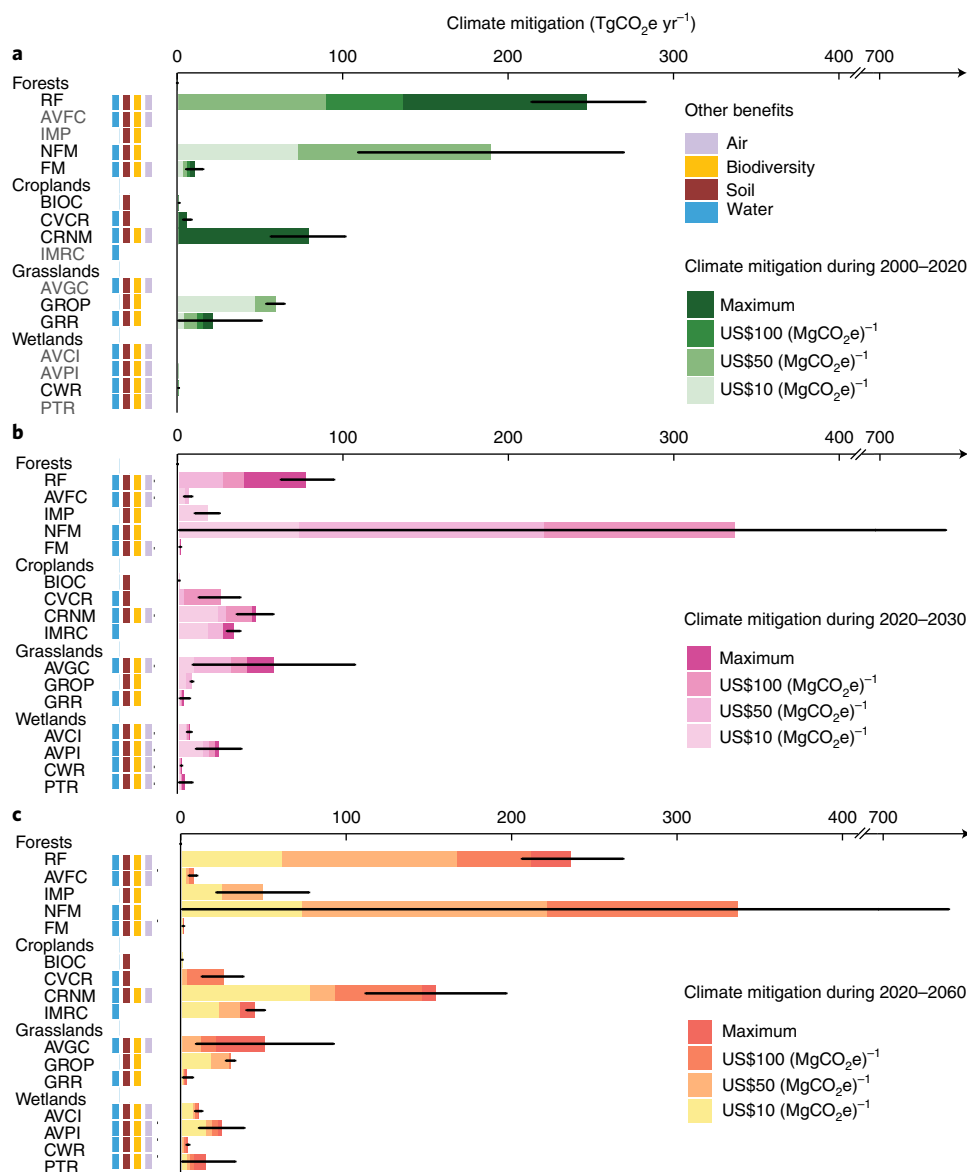
### Cropland ecosystems

Cropland NCS showed promising opportunities for climate mitigation via improved cropland management. During 2000–2020, the total mitigation from the three cropland pathways was 84 TgCO<sub>2</sub>yr<sup>-1</sup> (Fig. 1a), 14% of the overall historical flux of the nine NCS pathways. Cropland nutrient management decreased N<sub>2</sub>O emissions by 79 TgCO<sub>2</sub>yr<sup>-1</sup> from reduced nitrogenous fertilizer use and improved fertilizer production technology (Supplementary Table 3 and Extended Data Fig. 6). Cover crops (on 4.5 Mha of winter fallow) contributed 5 TgCO<sub>2</sub>yr<sup>-1</sup> through soil carbon sequestration. The mitigation capacity of biochar was minimal (0.5 TgCO<sub>2</sub>yr<sup>-1</sup>) as the amount of crop residues used for biochar production is small (0.11% of the total of 708 Mt yr<sup>-1</sup>).

In the future, the MAMP of the cropland pathways (including a new pathway of improved rice cultivation) could reach 104 TgCO<sub>2</sub>yr<sup>-1</sup> by 2030 and 223 TgCO<sub>2</sub>yr<sup>-1</sup> by 2060 (scenario setting in Supplementary Table 2) (Fig. 1b–c). These values are 1.2 and 2.6 times as large as the historical value, respectively, contributing 16% and 23% to the overall NCS potential of the 16 pathways. Specifically, the potential additional N<sub>2</sub>O emissions reduction through improved N management could be 46 TgCO<sub>2</sub>yr<sup>-1</sup> by 2030 and 153 TgCO<sub>2</sub>yr<sup>-1</sup> by 2060, assuming that our scenario of reducing N fertilizers by 13–49% would not affect crop yield<sup>19</sup>. The contribution from cover crops could increase to be 25 TgCO<sub>2</sub>yr<sup>-1</sup> if the maximum area of 15.1 Mha of winter fallow is applied with cover crops. Biochar would remain as a less important NCS pathway (0.1 TgCO<sub>2</sub>yr<sup>-1</sup>). By comparison, rice cultivation is extensive in China (30.5 Mha), and improved rice cultivation as a new NCS pathway could contribute 33–44 TgCO<sub>2</sub>yr<sup>-1</sup> in CH<sub>4</sub> emissions reductions in the next 10–40 years through improved soil management and drainage processing<sup>20</sup>.

### Grassland ecosystems

Grazing optimization and grassland restoration was estimated to be a net sink of 80 TgCO<sub>2</sub>yr<sup>-1</sup> during the period 2000–2020, contributing 13% to the overall mitigation capacity of the nine pathways (Fig. 1a), of which 59 TgCO<sub>2</sub>yr<sup>-1</sup> was from grazing optimization (fencing or sowing on an area of 99.6 Mha (ref.<sup>21</sup>)) and 21 TgCO<sub>2</sub>yr<sup>-1</sup> from grassland restoration (on 5.8 Mha cropland) (Fig. 1a and Supplementary Tables 2 and 3). In the future, the total additional MAMP from grassland ecosystems is estimated at 68–82 TgCO<sub>2</sub>yr<sup>-1</sup> during 2020–2060 (8–11% of the overall NCS potential) (Fig. 1b,c and scenario setting in Supplementary Table 2). Grassland grazing optimization could be applied on a smaller area in the future (15.6 Mha by 2030 and 62.4 Mha by 2060) and consequently would contribute a smaller NCS potential of 8 TgCO<sub>2</sub>yr<sup>-1</sup> and 29 TgCO<sub>2</sub>yr<sup>-1</sup>, respectively. For grassland restoration in cropland over steep slopes, the additional area available in the future would be only 0.54 Mha (Extended Data Figs. 1 and 2). Thus, the MAMP of grassland restoration would remain constant at 3 TgCO<sub>2</sub>yr<sup>-1</sup> during 2020–2060. Cropland expansion is the major cause of grassland conversion in China at a rate of 0.53 Mha yr<sup>-1</sup>. Avoided grassland conversion to cropland will provide a new mitigation opportunity, reducing an additional CO<sub>2</sub> emission of 50–57 TgCO<sub>2</sub>yr<sup>-1</sup> (Fig. 1b,c).



**Fig. 1 | Historical mitigation capacity and future NCS potential in China.** **a**, Historical capacity during 2000–2020. **b,c**, Future potential during 2020–2030 (**b**) and 2020–2060 (**c**). Light to dark colours of the bars indicate mitigation levels at the mitigation costs of US\$10, US\$50 and US\$100 (MgCO<sub>2</sub>e)<sup>-1</sup>, respectively. Black lines represent the 95% CI. Ecosystem service benefits (air, biodiversity, soil and water) linked with each NCS pathway are indicated by coloured short bars. Pathway names: Reforestation (RF), Avoided Forest Conversion (AVFC), Improved Plantation (IMP), Natural Forest Management (NFM), Fire Management (FM), Biochar (BIOC), Cover Crops (CVCR), Cropland Nutrient Management (CRNM), Improved Rice Cultivation (IMRC), Avoided Grassland Conversion (AVGC), Grazing Optimization (GROP), Grassland Restoration (GRR), Avoided Coastal Wetland Impacts (AVCI), Avoided Peatland Impacts (AVPI), Coastal Wetland Restoration (CWR), Peatland Restoration (PTR). See Supplementary Tables 1 and 2 for pathway definitions and extent of application. Note only nine pathways have mitigation capacities during 2000–2020, and the other seven pathways (in grey) do not have the historical capacities as no activities have been taken before 2020.

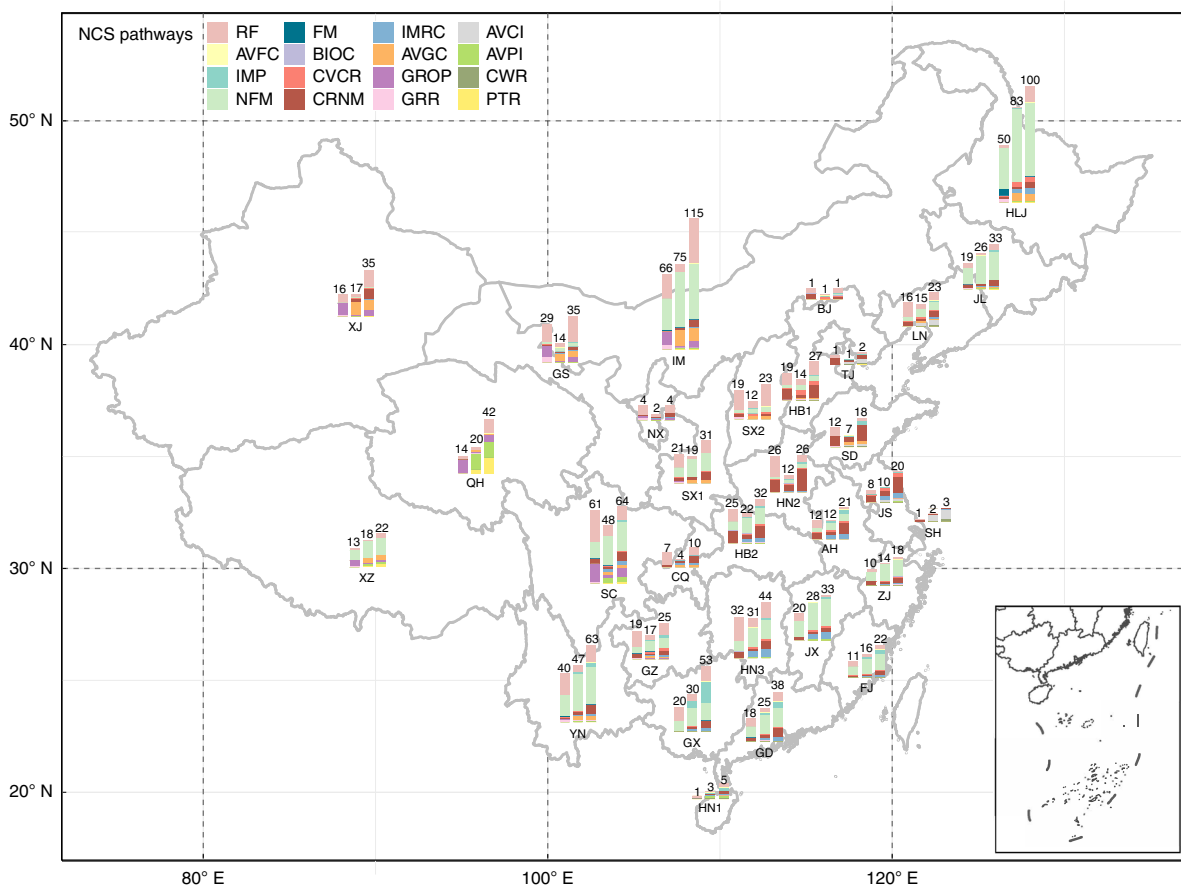
**Wetland ecosystems**

The mitigation capacity from wetland projects during 2000–2020 was negligible (<1 TgCO<sub>2</sub>e yr<sup>-1</sup>) compared with the other pathways (Fig. 1a), but shows great potential as NCS in the next decades (35 and 52 TgCO<sub>2</sub>e yr<sup>-1</sup> by 2030 and 2060, respectively (Fig. 1b,c), contributing 4–5% to the overall NCS potential of the 16 pathways), especially for peatland (Supplementary Table 3). Avoided peatland loss could potentially reduce CO<sub>2</sub> emissions 24 TgCO<sub>2</sub>e yr<sup>-1</sup> over the next 40 years (on 0.09–0.38 Mha of area). Peatland restoration by soil re-wetting could contribute an additional 4 and 14 TgCO<sub>2</sub>e yr<sup>-1</sup> mitigation potential (the net effect of decreasing CO<sub>2</sub> emissions and increasing carbon accumulation but increasing CH<sub>4</sub> emissions) by 2030 and 2060 (0.05

and 0.19 Mha), respectively (Fig. 1b,c). Coastal wetland restoration could sequester 2 and 4 TgCO<sub>2</sub>e yr<sup>-1</sup> (0.11 and 0.38 Mha). Avoided coastal wetland impacts (including salt marshes and sea grass beds) could reduce CO<sub>2</sub> emissions 6 and 10 TgCO<sub>2</sub>e yr<sup>-1</sup> by 2030 and 2060 (0.10 and 0.41 Mha), respectively. Although the loss rate of coastal ecosystems and wetlands is small (<0.01 Mha yr<sup>-1</sup>), they need extra attention because the carbon flux per unit area released from wetland loss is substantial (Fig. 1b,c and Supplementary Tables 2 and 3).

**Spatial distribution of the NCS**

The climate mitigation from the 16 NCS pathways shows large spatial differences across the country. Inner Mongolia, Heilongjiang,



**Fig. 2 | Historical mitigation capacity and future NCS potential by each NCS pathway across the provinces of China.** The numbers above each of the three bars for each province represent the total flux ( $\text{TgCO}_2\text{e.yr}^{-1}$ ) in the periods of 2000–2020, 2020–2030 and 2020–2060, respectively. AH, Anhui; BJ, Beijing; CQ, Chongqing; FJ, Fujian; GD, Guangdong; GS, Gansu; GX, Guangxi; GZ, Guizhou; HB1, Hebei; HB2, Hubei; HLJ, Heilongjiang; HN1, Hainan; HN2, Henan; HN3, Hunan; IM, Inner Mongolia; JL, Jilin; JS, Jiangsu; JX, Jiangxi; LN, Liaoning; NX, Ningxia; QH, Qinghai; SC, Sichuan; SD, Shandong; SH, Shanghai; SX1, Shaanxi; SX2, Shanxi; TJ, Tianjin; XJ, Xinjiang; XZ, Xizang; YN, Yunnan; ZJ, Zhejiang. Base map from the National Earth System Science Data Center, National Science and Technology Infrastructure of China (<http://www.geodata.cn>).

Sichuan and Yunnan are the top four provinces with the highest levels of historical achieved capacity and future potential (Fig. 2). Except for some provinces in Northwest and East China, natural forest management and/or reforestation contributes the most to the overall NCS. For Xinjiang and Qinghai, grazing optimization had the biggest contribution to the historical flux, and grassland and peatland management will be important NCS opportunities in the future. In some provinces in Central and East China (including Henan, Hubei, Hunan, Shandong, Anhui, Jiangxi and Jiangsu), cropland nutrient management and improved rice cultivation are also important options for future NCS. Improved plantations are non-negligible in Guangxi province.

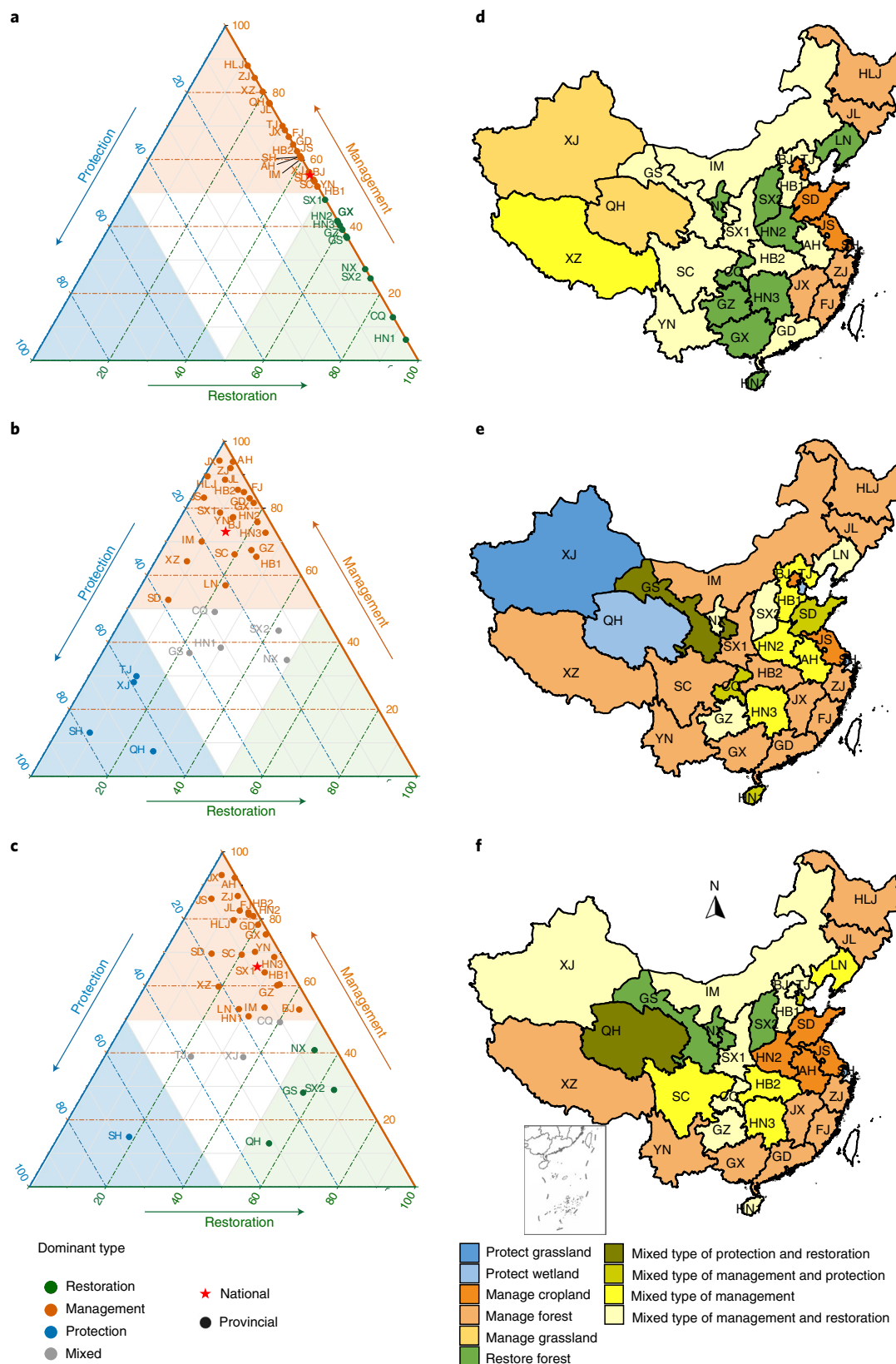
At the national level, the dominant type of the NCS was restoration and improved management before 2020, but it would shift towards improved management in future decades, with protection becoming more important (Fig. 3a–c, the type of NCS defined in Methods). At the provincial level, ten NCS types were further identified as the predominant options, including six single types and four mixed or combined types (Fig. 3e,f), indicating the need for diverse NCS activities.

### Cost effectiveness

By using marginal abatement cost (MAC) curves, the climate mitigation at three cost thresholds of each NCS pathway was estimated. During 2000–2020, only  $125 \text{ TgCO}_2\text{e.yr}^{-1}$  (20% of the total) was

achieved at a mitigation cost below  $\text{US}\$10 (\text{MgCO}_2\text{e})^{-1}$  (Fig. 1a–c). In the future,  $165 \text{ TgCO}_2\text{e.yr}^{-1}$  (26%) and  $298 \text{ TgCO}_2\text{e.yr}^{-1}$  (30%) out of the total NCS will be achievable by 2030 and 2060, respectively, at  $\text{US}\$10 (\text{Mg CO}_2\text{e})^{-1}$ . At a mitigation cost of  $\text{US}\$50 (\text{MgCO}_2\text{e})^{-1}$ ,  $354 \text{ TgCO}_2\text{e.yr}^{-1}$  (58%),  $390 \text{ TgCO}_2\text{e.yr}^{-1}$  (62%) and  $641 \text{ TgCO}_2\text{e.yr}^{-1}$  (65%) of the total NCS are available during 2000–2020, 2020–2030 and 2020–2060, respectively. For mitigation costs up to  $\text{US}\$100 (\text{Mg CO}_2\text{e})^{-1}$ ,  $406 \text{ TgCO}_2\text{e.yr}^{-1}$  (66%),  $573 \text{ TgCO}_2\text{e.yr}^{-1}$  (90%) and  $898 \text{ TgCO}_2\text{e.yr}^{-1}$  (91%) are achievable. Natural forest management is the most cost-effective option at all of the three mitigation costs and will achieve the highest MAMP ( $336 \text{ TgCO}_2\text{e.yr}^{-1}$ ) at  $\text{US}\$100 (\text{Mg CO}_2\text{e})^{-1}$  during 2020–2060 (Fig. 1a–c). The portion of achievable NCS at the three cost thresholds is similar to that of the United States but higher than that of Canada. The US total NCS is  $1.2 \text{ PgCO}_2\text{e.yr}^{-1}$  during 2015–2035 (19% of industrial  $\text{CO}_2$  emissions of the 1990–2018 level), 25%, 76% and 91% of which would be achieved at  $\text{US}\$10$ ,  $\text{US}\$50$  and  $\text{US}\$100 (\text{MgCO}_2\text{e})^{-1}$ , respectively<sup>22</sup>. For Canada, the total NCS is  $78 \text{ TgCO}_2\text{e.yr}^{-1}$  during 2021–2030 (100% of all heavy industry emissions of the 2018 level); 12%, 34% and 51% of which would be available at  $\text{CAN}\$10$ ,  $\text{CAN}\$50$  and  $\text{CAN}\$100 (\text{MgCO}_2\text{e})^{-1}$ , respectively<sup>23</sup>.

Besides climate mitigation, the NCS measures bring co-benefits, including improving biodiversity, air purification, soil enrichment and water retention<sup>24,25</sup> (Fig. 1). The value of these co-benefits is not accounted for in our estimation of cost effectiveness of



**Fig. 3 | NCS pathway types at the provincial level for the three periods. a–c**, Proportional distribution of NCS types during 2000–2020 (**a**), 2020–2030 (**b**) and 2020–2060 (**c**). Four types of pathways are classified: ‘Restoration’ (>50% restoration), ‘Protection’ (>50% protection), ‘Management’ (>50% management) and ‘Mixed’ (no pathway type contributes the majority). The red star represents the national barycentre of NCS types. **d–f**, The provinces are further classified into ten groups on the basis of the ecosystem type of pathway contributing the most mitigation potential during 2000–2020 (**d**), 2020–2030 (**e**) and 2020–2060 (**f**). Mixed types are not specified ecosystem types as they contain many combinations. Base maps in **d–f** from the National Earth System Science Data Center, National Science and Technology Infrastructure of China (<http://www.geodata.cn>).

**Box 1 | Baseline setting and NCS estimation**

Existing NCS estimates for China, including the national assessment by The Nature Conservancy<sup>27</sup> and the China Country Report by Nature4Climate<sup>28</sup>, refer mainly to the global assessment by ref. <sup>1</sup>, in which the baseline is 2000s–2010s and scenarios include 2010s–2030. Setting 2000–2020 as a baseline in this study partly makes the estimate of the future NCS potential smaller than their studies for the same target year 2030 because for the specific time point in 2030, the NCS implementation extent counted in the assessments is different. In particular, reforestation was implemented on a large land area of 44.7 Mha during 2000–2020 (sequestering 247 TgCO<sub>2</sub>yr<sup>-1</sup> by 2020) and will continue to sequester carbon after 2020 (which we refer to as the legacy effect). The post-2020 legacy carbon sink from previous reforestation is projected to be 484 TgCO<sub>2</sub>yr<sup>-1</sup> by 2030 and 494 TgCO<sub>2</sub>yr<sup>-1</sup> by 2060, which will be counted in China's future land carbon budget but is excluded from our estimates of the future NCS potential as the essence of NCS is to seek new opportunities. Counting the legacy effect and the future potential will counterbalance a higher percentage of contemporary CO<sub>2</sub> emissions (11–12%) during 2020–2030. Therefore, baseline setting is critical for defining and projecting future activities in NCS assessments and making comparisons among studies. In this research, setting 2000–2020 as the baseline is to evaluate the contribution of the 20 yr efforts of previous ecological projects to climate mitigation and establish how much additional NCS potential we could get in a shorter (10 years) and longer (40 years) term if we take actions from now (corresponding to the release of the updated NDCs in 2021 and the goals of peak in CO<sub>2</sub> emissions before 2030 and net carbon neutrality by 2060).

the NCS, but they will save economic costs and improve human well-being<sup>26</sup>.

**Calibration upon the global assessment for China**

A relative comparison between our estimates and those in ref. <sup>1</sup> can be made in terms of implementation extent and flux rate (per unit area) within a given period (Extended Data Fig. 7 and Box 1). In ref. <sup>1</sup>, the estimated MAMP of reforestation for China is as high as 1,257 TgCO<sub>2</sub>e yr<sup>-1</sup> (2010–2030), five times our estimate (247 TgCO<sub>2</sub>yr<sup>-1</sup>, 2000–2020), mainly because they used a much higher value for carbon sequestration rates (4.14 MgC ha<sup>-1</sup>yr<sup>-1</sup>). They assumed that 25–30% of total NCS by reforestation can be achieved at US\$100, that is, 319 TgCO<sub>2</sub>yr<sup>-1</sup> (refs. <sup>27,28</sup>). We estimated that 55% (136 TgCO<sub>2</sub>yr<sup>-1</sup>) of the total NCS (247 TgCO<sub>2</sub>yr<sup>-1</sup>) can be realized at US\$100 during 2000–2020 on the basis of our MAC curves using actual data from regions that implemented reforestation in China (Extended Data Fig. 7). The CO<sub>2</sub> sink of natural forest management in 2000–2020 is 189 TgCO<sub>2</sub>yr<sup>-1</sup> in this study, versus only 35 TgCO<sub>2</sub>yr<sup>-1</sup> in ref. <sup>1</sup>. This large difference is because we separated natural forests into different age classes with different sequestration rates (40–90 years) to obtain a weighted mean carbon sequestration rate (0.71–1.25 MgC ha<sup>-1</sup>yr<sup>-1</sup>), whereas ref. <sup>1</sup> set sequestration rates to a mean value (0.14–0.39 MgC ha<sup>-1</sup>yr<sup>-1</sup>) uniform across all forests. Much higher NCS estimates of biochar are reported by the Natural Conservancy<sup>27</sup> (65 TgCO<sub>2</sub>e yr<sup>-1</sup> at the price of US\$100) and ref. <sup>29</sup> (500 TgCO<sub>2</sub>e yr<sup>-1</sup>), who assumed that 14% or 100% of China's crop residues can be used to produce biochar in the future, but this fraction is actually less than 1%, and it will be a gradual process to transform crop residues to produce a large amount of biochar, requiring a change of regime of crop residue use. Based on this, biochar NCS is very small (<1 TgCO<sub>2</sub>e yr<sup>-1</sup>) in both historical and future estimates in our study (Extended Data Fig. 7).

The differences between our study and the global studies indicate that baseline setting as well as the use of regional data can greatly impact NCS assessment. Thus, well-calibrated national assessments are necessary to improve upon rough global estimates. For further comparative analysis, see the corresponding sections in each of the individual pathways in the Supplementary Information.

**The implications**

To achieve the future maximum potential of NCS and enhance the co-benefits of multiple ecosystem services, it is critical that integrated land planning and management optimization is applied at different jurisdictional levels and spatial scales, especially since the NCS pathways will be implemented on such a large land area nationwide (Extended Data Figs. 1 and 2). Specifically, overall land-use planning should focus on systematic layout (total area control) of land restoration<sup>30</sup> and replacement<sup>31</sup> at the national level on the basis of accurate land surveys, emphasizing coordination between restoration/protection and management at the provincial or regional level and highlighting livelihood and realization of social justice at the local level by implementing ecological compensation<sup>26</sup>. The case of the Loess Plateau of China—the pioneer area of the Grain for Green Project—has proved that food security can be maintained through improved management practices such as improving nutrient use efficiency, water-saving irrigation and construction of terraces and check dams<sup>32</sup> while at the same time capturing carbon in vegetation and soil and reducing soil sediment in the Yellow River<sup>33,34</sup>. We also suggest that the government should set a percentage target of NCS based on the resource status of each region/province, continuing to strictly implement ecosystem protection policies as the damage to ecosystems will outweigh the benefits of managing and restoring without protection<sup>35</sup>. Alongside protection, improving management of ecosystems and promoting ecological restoration should be implemented for maintaining the long-term benefits of NCS. Our spatial maps clearly show different opportunity options in each province throughout the country. At the national or provincial level, since natural resource abundance and economic capital are limited, it is important for policymakers to transform their thinking from 'expanding the extent of ecosystems' to 'improving the benefits per unit land area', maintaining the overall strength of investment, fair and effective fund distribution (for example, via improving ecosystem services payment system)<sup>36</sup> and management and technological creativity (for example, improving the fertilizer production process or developing digital fencing).

**Challenges and next steps**

Climate change and ecosystem spatial shifts may bring great uncertainties to the carbon sequestration rates estimated on the basis of the existing spatial locations of the samples. The feedback between climate change and ecosystem change (such as forest albedo, particularly for the temperate zone and the boreal forest on the north-east) may also reduce the mitigation potential of the NCS<sup>37</sup>. These aspects, related to long-term ecosystem change and climate feedback, should be further explored for better estimating future NCS potential. In addition, due to limited data availability, biomass and soil carbon or other GHGs were not fully considered. Other pathway options, including actions to avoid carbon loss due to natural disturbances (such as pests, diseases and climate extremes), or NCS potential from managing the urban green infrastructure, livestock and aquaculture sectors, need be quantified. In addition, the inclusion of co-benefits brought by NCS will greatly change the assessment of cost effectiveness. Finally, the implementation of an NCS plan will also be affected by national economic development level, population change, policies and investment, pandemic events (such as COVID-19) and other socioeconomic factors.

In this work, we showed that China's NCS could counterbalance 6% (11–12% if including legacy effect) of industrial carbon

emissions between now and 2030. This modest proportion highlights that energy transformation and the rapid application of low-carbon technologies are urgent priorities for climate mitigation. Nevertheless, NCS pathways can still make an important contribution through additional carbon sequestration or avoided GHG emissions, buying time for the development and implementation of new technologies. Multilevel governance strategies that consider the spatial heterogeneity of the NCS pathways are needed to increase the synergies among multiple NCS pathways for realizing climate mitigation and co-benefits of ecosystem services.

### Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41558-022-01432-3>.

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## Methods

This study presents a comprehensive quantification of carbon sequestration as well as CO<sub>2</sub>/CH<sub>4</sub>/N<sub>2</sub>O emissions reductions from terrestrial ecosystems based on multiple sources of data from literature, inventories, public databases and documents. The pathways considered ecosystem restoration and protection from being converted into cropland or built-up areas, reforestation, management with improved nitrogen use in cropland, restricted deforestation, grassland recovery, reducing risk from forest wildfire and others. Here we describe the cross-cutting methods that apply across all 16 NCS pathways. The definitions, detailed methods and data sources for evaluating individual pathways can be found in the Supplementary Information.

**Cross-cutting methods. Baseline setting.** We set 2000 as the base year because the large-scale national ecological projects, such as the Grain for Green Project, were started since then. We first evaluate the historical mitigation capacity during 2000–2020, which is the first 20 years of implementing the projects. From this procedure we can determine how much mitigation capacity has been realized through the previous projects in the past two decades and to what extent additional actions can be made after 2020. Relative to the baseline 2000–2020, we then evaluate the maximum potentials of the NCS mitigation in the future 10 (2020–2030) and 40 (2020–2060) years, corresponding to the timetable of China's NDCs: carbon peak before 2030 and carbon neutrality by 2060.

The settings of baseline in this study are different from the existing assessments (2000s–2010s as a baseline and 2010–2025/2030/2050 as scenarios)<sup>1,22,23,27,28</sup>. Baseline sets the temporal and spatial reference for NCS pathway scenarios, which may have a great impact on the NCS estimates. Notably, NCS actions during 2000–2020 will have a great impact in the future periods, which we refer to as the 'legacy effect'. The legacy effect itself, mainly reforestation, is independent of being assessed, but it is conceptually attributed to natural flux and excluded from future NCS potential estimates.

**Maximum potential.** The MAMP refers to the additional CO<sub>2</sub> sequestration or avoided GHG emissions measured in CO<sub>2</sub> equivalents (CO<sub>2</sub>e) at given flux rates in a period on the maximum extent to which the stewardship options are applied (numbers are expressed as TgCO<sub>2</sub>e yr<sup>-1</sup> for individual pathways and PgCO<sub>2</sub>e yr<sup>-1</sup> for national total) (Extended Data Fig. 1 and Supplementary Table 2). 'Additional' means mitigation outcomes due to human actions taken beyond business-as-usual land-use activities (since 2020) and excluding existing land fluxes not attributed to direct human activities<sup>1</sup>. The MAMP of CH<sub>4</sub> and N<sub>2</sub>O are accounted by three cropland and wetland pathways (cropland nutrient management, improved rice cultivation and peatland restoration). We adopt 100 yr global warming potential to calculate the warming equivalent for CH<sub>4</sub> (25) and N<sub>2</sub>O (298), respectively<sup>38,39</sup> because these values are used in national GHG inventories, although some researchers have argued that using the fixed 100 yr global warming potential to calculate the warming equivalents may be problematic because they cannot differentiate the contrasting impacts of the long- and short-lived climate pollutants<sup>39</sup>. Because the flux rate of the GHG by ecosystems may vary with the time of recovery or growth, the MAMP may also change for different periods even given the same extent.

The 'maximum' is constrained by varied factors across the NCS pathways. We constrain forest and grassland restoration by the rate of implementation, farmland red line and tree surviving rate (Extended Data Fig. 2). Surviving rate here is the ratio of the area with increased vegetation cover due to reforestation to the total reforestation area. The farmland red line refers to 'the minimum area of cultivated land' given by the Ministry of Land and Resources of China. It defines the lowest limit, and the current red line is ~120 Mha. It is a rigid constraint below which the total amount of cultivated land cannot be reduced. From this total amount, there is provincial farmland red line. This red line sets a constraint on the implementation of the NCS pathways associated with land-use change. We set the future scenario of farmland area that can be used for grassland or forest restoration on the basis of the provincial farmland red line. Basic farmland is closely related to national food security. By 2050, China's population is predicted to decrease slightly, but with economic development, the per capita demand for food may increase<sup>40</sup>. We assume that the food production in the future can meet the food demand via increasing agricultural investment and technological advancement. The N fertilizer reduction scenario is set to be below the level 60%, under which crop yield is not significantly affected<sup>19</sup>, because N fertilizer is surplus in many Chinese croplands. For timber production, we assume that the demand for timber can be met if the production level is maintained at the level of 2010–2020 (83.31 million m<sup>3</sup> yr<sup>-1</sup>). As deforestation of natural forests is 100% forbidden since 2020, the future timber will come mainly from tree plantations. For grazing optimization, we assume that livestock production is not affected by grassland fencing due to refined livestock management such as improving feed nutrient and fine-seed breeding<sup>41</sup>.

The areas of historical NCS implementation during 2000–2020 were estimated using statistical data, published literature and public documents, with a supplement from remote-sensing data. The flux rates were obtained either by directly using the values from multiple literature sources or from estimates using the empirical formulae. For the estimates of future NCS potential, the flux rate and extent of the pathway were determined on the basis of the baseline (2000–2020). The extent is assumed to be achieved by using the same rate but limited by the multiple constraints

stated in the preceding unless the implementation scopes have been reported in national planning documents. We estimate the legacy effect by multiplying the implementation area in the past by the flux rates in the future two periods.

**Saturation.** The future mitigation potential that we estimate for 2030 and 2060 will not persist indefinitely because the finite potential for natural ecosystems to store additional carbon will saturate. For each NCS pathway, we estimate the expected duration of the potential for sequestration at the maximum rate (Supplementary Table 3). Forests can continue to sequester carbon for 70–100 years or more. Restored grasslands and fenced grasslands can continue to sequester carbon for >50 years. Forest-fire management and cover crops can continue to sequester carbon for 40–50 years or more. Sea grasses and peatlands can continue to sequester carbon for millennia. Avoided pathways do not saturate as long as the business-as-usual cases indicate that there are potential areas for avoided losses of ecosystems. In this case, sea grass and salt marsh would disappear entirely after 64 years, but it would be 100–300 years or more for forest, grassland and peatland.

**Estimation of uncertainties.** The extent (area or biomass amount) and flux (sequestration or reduced emission per area or biomass amount in unit time) are considered to estimate uncertainty of the historical mitigation capacity or future potential for each NCS pathway. We use the IPCC approaches to combine uncertainty<sup>42</sup>. Where mean and standard deviation can be estimated from collected literature, 95% CIs are presented on the basis of multiple published estimates. Where a sample of estimates is not available but only a range of a factor, we report uncertainty as a range and use Monte Carlo simulations (with normal distribution and 100,000 iterations) to combine the uncertainties of extent and flux (IPCC Approach 2). The overall uncertainties of the 16 NCS pathways were combined using IPCC Approach 1<sup>42</sup>. If the extent estimate is based on a policy determination, rather than an empirical estimate of biophysical potential, we do not consider it a source of uncertainty.

**MACs.** The economic/cost constraints refer to the amount of NCS that can be achieved at a given social cost. The MAC curve is fitted according to the total publicly funded investment and total mitigation capacity or potential during a period. The MAC curves are drawn to estimate the historical mitigation or MAMP at the cost thresholds of US\$10, US\$50 and US\$100 (MgCO<sub>2</sub>e)<sup>-1</sup>, respectively. The trading price in China's current carbon market is ~US\$10 USD (as the minimum cost<sup>43</sup>), and the cost-effective price point<sup>44,45</sup> to achieve the Paris Agreement goal of limiting global warming to below 2 °C above pre-industrial levels is US\$100 (as the maximum cost). A carbon price of US\$50 is regarded as a medium value<sup>4,46</sup>. For the pathways of reforestation, avoided grassland conversion, grazing optimization and grassland restoration, we collected the statistical data of investments in China from 2000 to 2020 and estimated the affordable MAMP below the three mitigation costs. Due to data limitations, the points used for fitting the MAC curve are values for cost (invested funds) and benefit (mitigation capacity) in each of the provinces. We rank the ratio of benefit to cost in a descending order to obtain the maximum marginal benefit for MAC by assuming that NCS measures are first implemented in the region with the highest cost/benefit rate. We refer to the investment standard before 2020 as the benchmark and estimate the cost of each pathway for the future periods with discount rates of 3% and 5%, respectively. The social discount rate 4–6% is usually used as a benchmark discount value in carbon price studies in China compared with lower scenarios (for example, 3.6%)<sup>46,47</sup>. In a global study for estimating country-level social cost of carbon, 3% and 5% are used for scenario analysis<sup>48</sup>. Note that the mean value from the two discount rates was used in presenting the results. For the other pathways where investment data cannot be obtained, we refer to relevant references to estimate MAC. All the cost estimates are expressed in 2015 dollars, transformed on the basis of the Renminbi and US dollar exchange rate of the same year. The year 2015 represents a relatively stable condition of economic increase over the past decade (2011–2020) in China (the increase rate of gross domestic product (GDP) in 2015 is similar to the 10 yr mean). In the cases when the MAC curves exceed the estimated maximum potentials in the period, we identify the historical capacity or the MAMP as limited by the biophysical estimates.

**Additional mitigation required to meet Paris Agreement NDCs.** On 28 October 2021, China officially submitted 'China's Achievements, New Goals and New Measures for Nationally Determined Contributions' ('New Measures 2021' hereafter) and 'China's Mid-Century Long-Term Low Greenhouse Gas Emission Development Strategy' to the Secretariat of the United Nations Framework Convention on Climate Change as an enhanced strategy to China's updated NDCs (first submission in 2015). The goal of China's updated NDCs is to strive to peak CO<sub>2</sub> emissions before 2030 and achieve carbon neutralization by 2060. It specified the goals to include the following: before 2030, China's carbon dioxide emissions per unit of GDP are expected to be more than 65% lower than that in 2005, and the forest stock volume is expected to be increased by around 6.0 (previously 4.5) billion m<sup>3</sup> over the 2005 level. In the 'New Measures 2021'<sup>19</sup> and 'Master Plan of Major Projects of National Important Ecosystem Protection and Restoration (2021–2035)<sup>15</sup>, many NCS-related opportunities are proposed to consolidate the carbon sequestration of ecosystems and increase the future NCS potential, including protecting the existing ecosystems, implementing engineering to precisely improve forest quality,



continuously increasing forest area and stock volume, strengthening grassland protection and recovery and wetland protection and improving the quality of cultivated land and the agricultural carbon sinks.

**Industrial CO<sub>2</sub> emissions.** The historical CO<sub>2</sub> emissions data from 2000 to 2017<sup>49,50</sup> are used as the benchmark of industrial CO<sub>2</sub> emissions during 2000–2020. For future projections, we use the peak value of the A1B2C2 scenario (in the range of 10,000 to 12,000 Mt) in 2030 from ref. <sup>11</sup>. We assume that CO<sub>2</sub> emission increases linearly from 2017 to 2030.

**Characterizing co-benefits.** NCS activities proposed in the future measures or plans may enhance co-benefits. Four generalized types of ecosystem services are identified: improving biodiversity, water-related, soil-related and air-related ecosystem services (Fig. 1). Biodiversity benefits refer to the increase in different levels of diversity (alpha, beta and/or gamma diversity)<sup>51</sup>. Water, soil and air benefits refer to flood regulation and water purification, improved fertility and erosion prevention, and improvements in air quality, respectively, as defined in the Millennium Ecosystem Assessment<sup>52</sup>. The evidence that each pathway produces co-benefits from one or more peer-reviewed publications was collected through reviewing the literature (see the details for co-benefits of each pathway in Supplementary Information).

**Mapping province-level mitigation.** The data for extent of implementing forest pathways are obtained from the statistical yearbook and reported at the province level. To be consistent with the forest pathways, the other pathways were also aggregated to the provincial-level estimate from the spatial data. If the flux data were available in different climate regions, the provinces are first assigned to climate regions. When a province spans multiple climate zones, the weight value is set according to the proportion of area, and finally an estimated value of rate was calculated (for fire management, some grassland and wetland pathways). For the forest pathways, we first collected the flux-rate data from reviewing literature and then averaged these flux rates to region/province. The flux rates for reforestation and natural forest management were calculated separately by province and age group. Similarly, specified flux rates are applied for different times after ecosystem restoration or conversion for other pathways.

**Classification of NCS types.** Three types of NCS pathways were classified: protection (of intact natural ecosystems), improved management (on managed lands) and restoration (of native cover)<sup>35</sup>. In our study, four (AVFC, AVGC, AVCI, AVPI), eight (IMP, NFM, FM, BIOC, CVCR, CRNM, IMRC, GROF) and four (RF, GRR, CWR, PTR) NCS pathways were identified as protection, management and restoration types, respectively (Supplementary Table 1). These pathways can be further divided into groups of 'single' type or 'mixed' type according to their contribution to individual pathways. Specifically, in a certain area, when the mitigation capacity of a certain pathway accounts for more than 50% of the total, it is regarded as a single or dominant NCS type; if no single pathway accounts for more than 50%, it is a mixed type, named by the top pathways whose NCS sum exceeds 50% of the total mitigation capacity.

## Data availability

The base map is available from National Earth System Science Data Center, National Science and Technology Infrastructure of China (<http://www.geodata.cn>). All data generated or analysed during this study are provided with data sources in the Supplementary Information.

## Code availability

We acknowledge the ArcMap Software version 10.6 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources>), R Software Foundation version R x64 4.0.3 (<https://mirrors.tuna.tsinghua.edu.cn/CRAN/>) and Python Software Foundation: Python Language Reference, version 3.7.7 (<http://www.python.org>).

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## Author contributions

B.F., H.T. and N.L. co-designed and coordinated this research with substantial inputs from all authors; N.L., H.Y., S.C., Y.L., X.L., M.W., Z.L. and L.Z. performed data collections, calculations and analysis. S.P., P.C. and P.S. contributed interpretation of the results and editing of the manuscript. All authors discussed and commented on the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

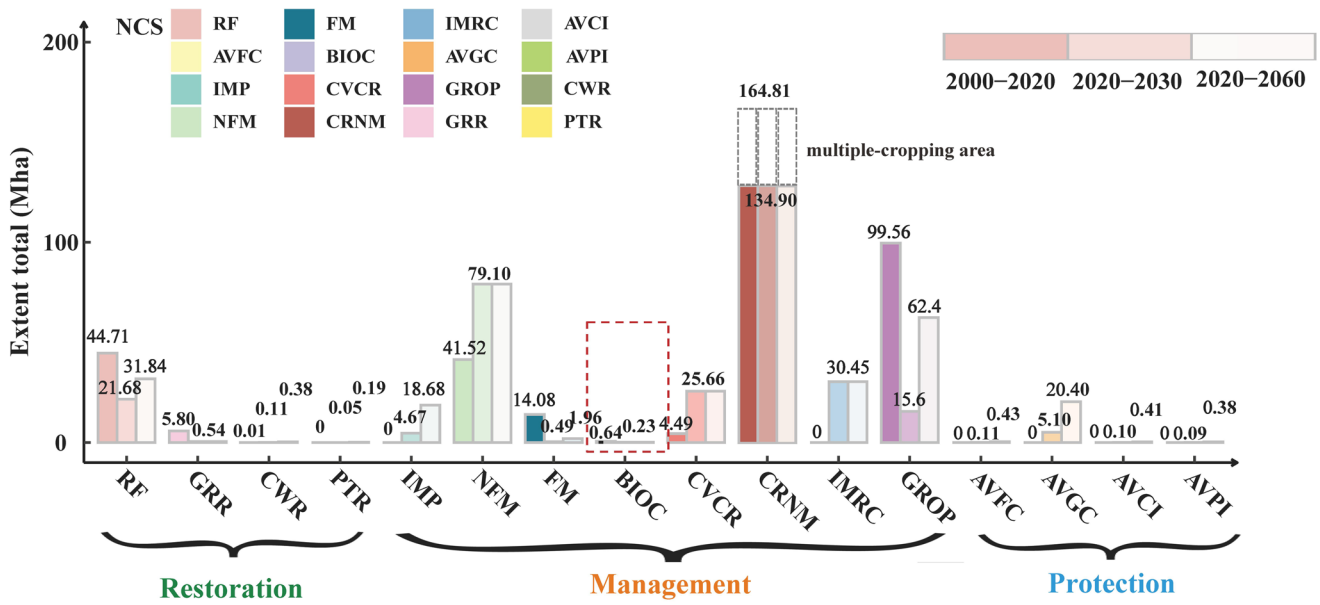
**Extended data** is available for this paper at <https://doi.org/10.1038/s41558-022-01432-3>.

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s41558-022-01432-3>.

**Correspondence and requests for materials** should be addressed to Bojie Fu.

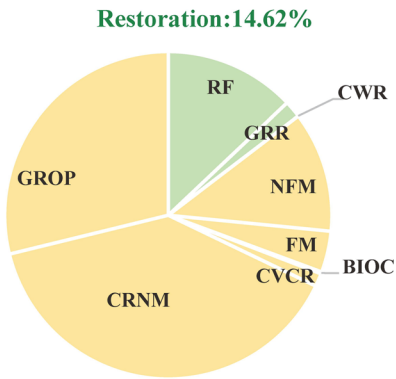
**Peer review information** *Nature Climate Change* thanks C. Ronnie Drever, Peter Ellis and Yuanyuan Yi for their contribution to the peer review of this work.

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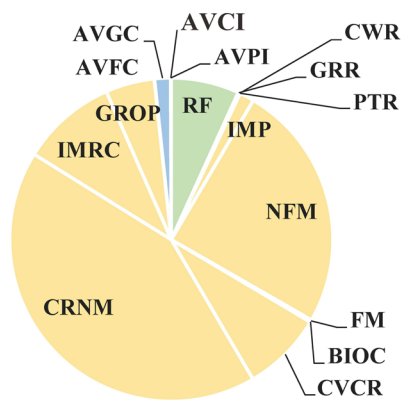
Extent ratio of 16 NCS pathways:

2000-2020

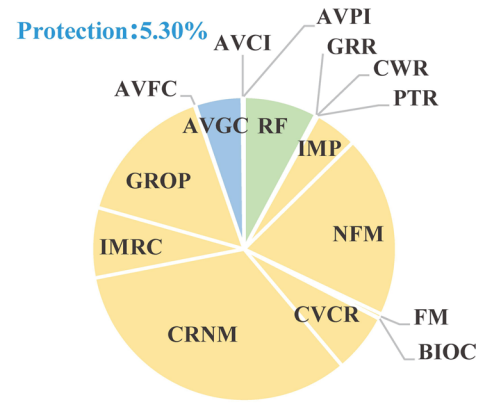


Protection: 1.69%

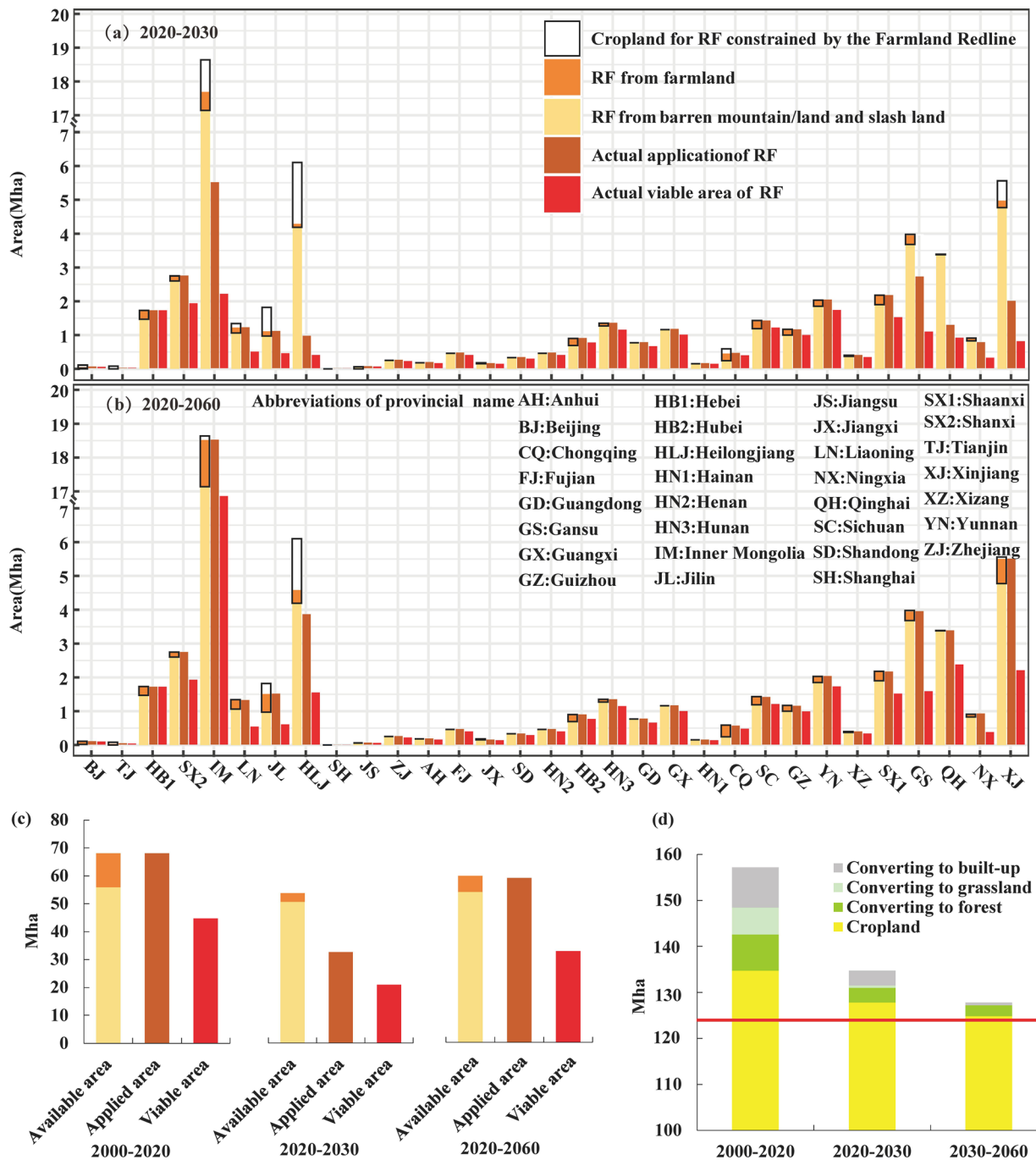
2020-2030



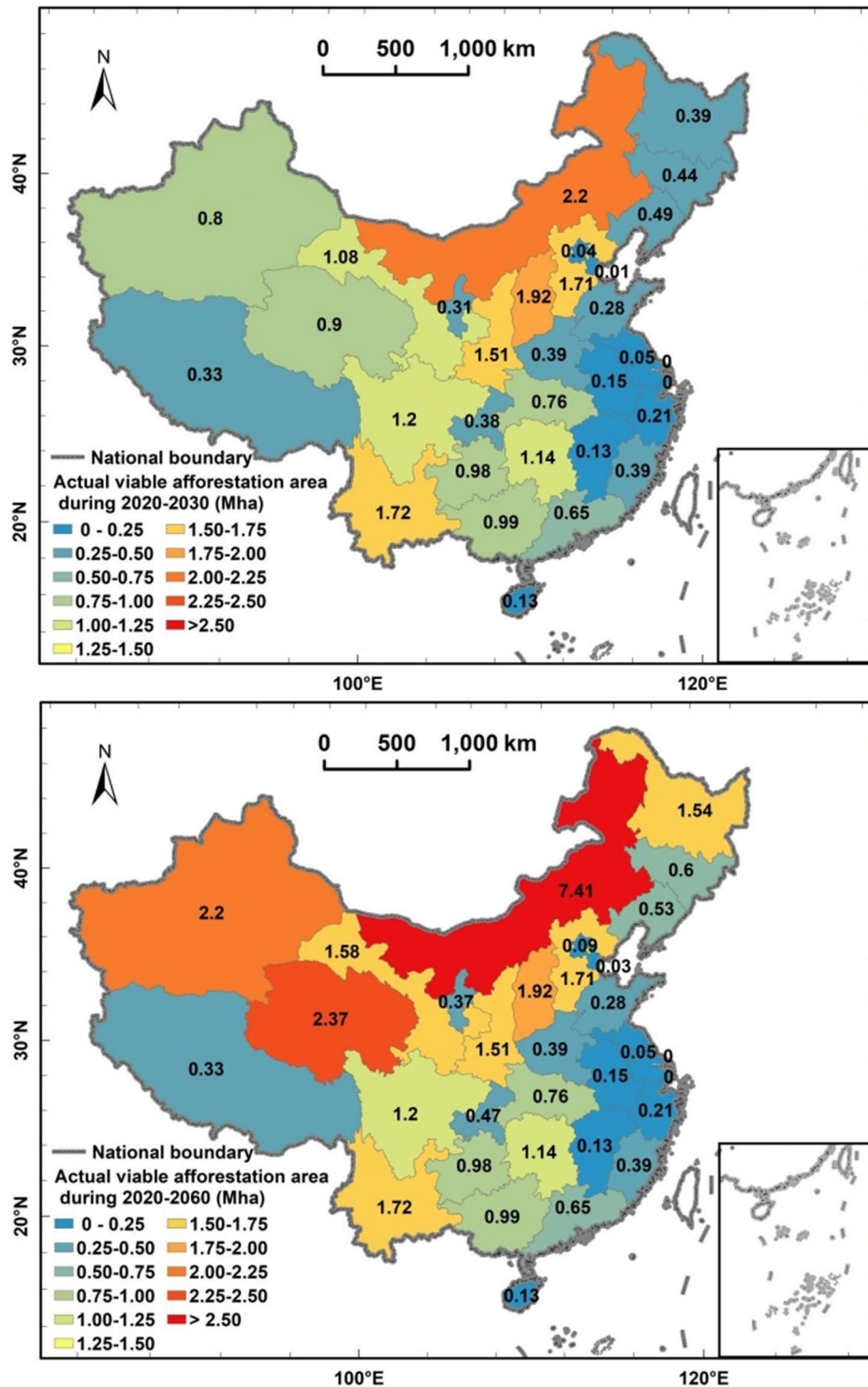
2020-2060



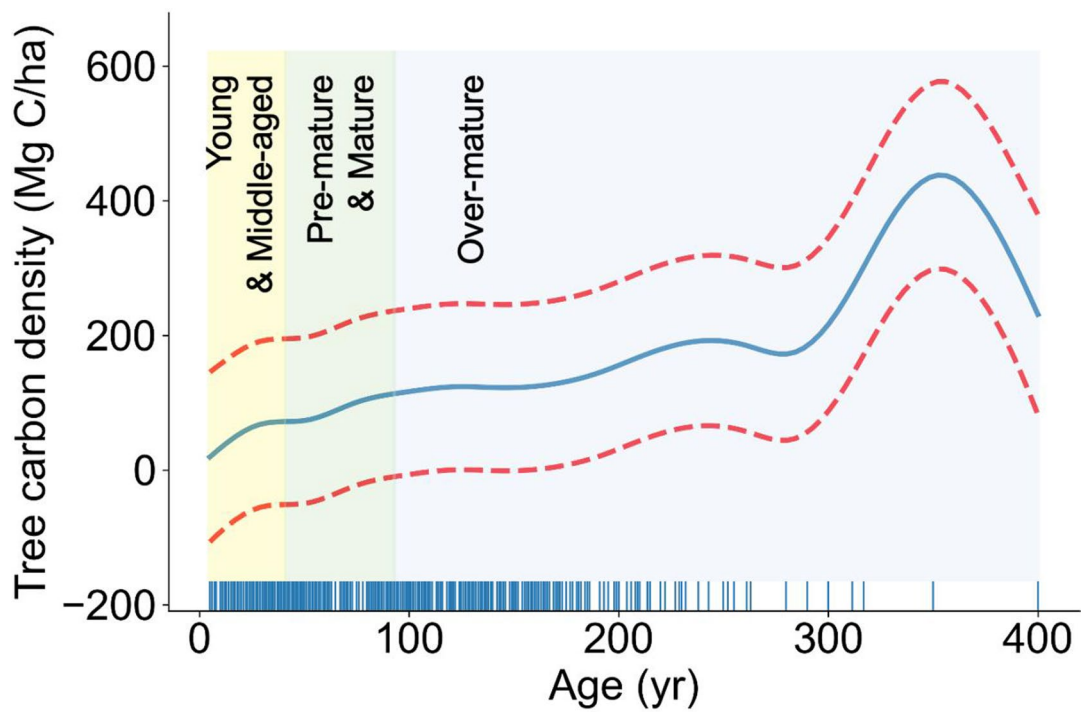
**Extended Data Fig. 1 | The extents of land area that adopt the different NCS pathways.** The numbers in the bar chart represent the applicable extents (except for BIOC) of the different pathways during each of the three periods. Note: the areas that implement CVCR and IMRC are some proportions of the total area in CRNM. The area for CRNM is the cumulative area of sowing, including rotation (that is, the dotted line bars for CRNM), and therefore is greater than the total cropland area. The numbers for BIOC are not for area but the mass of crop residue (Tg dry mass) for biochar production. Pathway name abbreviations please see Fig. 1.



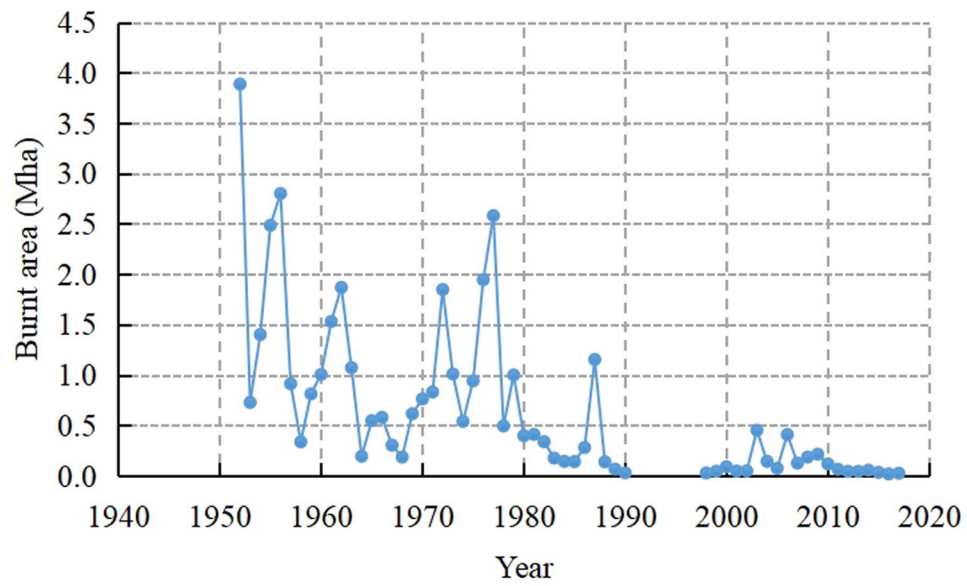
**Extended Data Fig. 2 | Areas available for forest and grassland restoration.** Area available for reforestation constrained by the farmland red line, water stress, and urbanization at the provincial level during (a) 2020-2030, (b) 2020-2060, and (c) the national level. Farmland area available for grassland restoration constrained by the *Farmland Red Line* and urbanization (d). The remaining cropland area (yellow bar) is approaching the *Farmland Red Line* (123.44 Mha, the red line). Here cropland gain converting from other land cover types is not considered as these gains usually come from low-quality lands, which should be avoided in the future<sup>31</sup>.



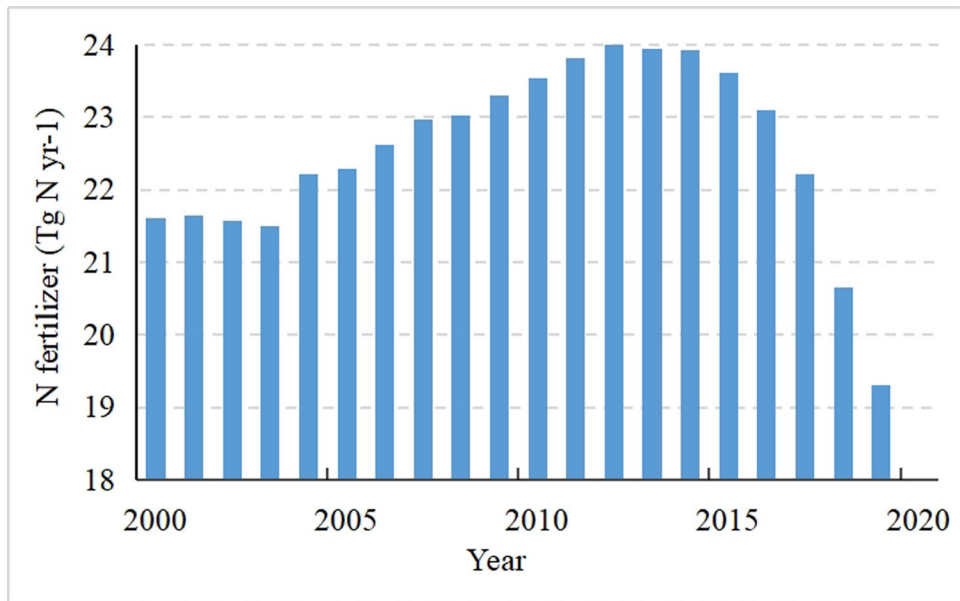
**Extended Data Fig. 3 | Spatial distribution of projected actual surviving area of reforestation during 2020-2030 and 2020-2060.** The number represents the area for each province. Base map from the National Earth System Science Data Center, National Science and Technology Infrastructure of China (<http://www.geodata.cn>).



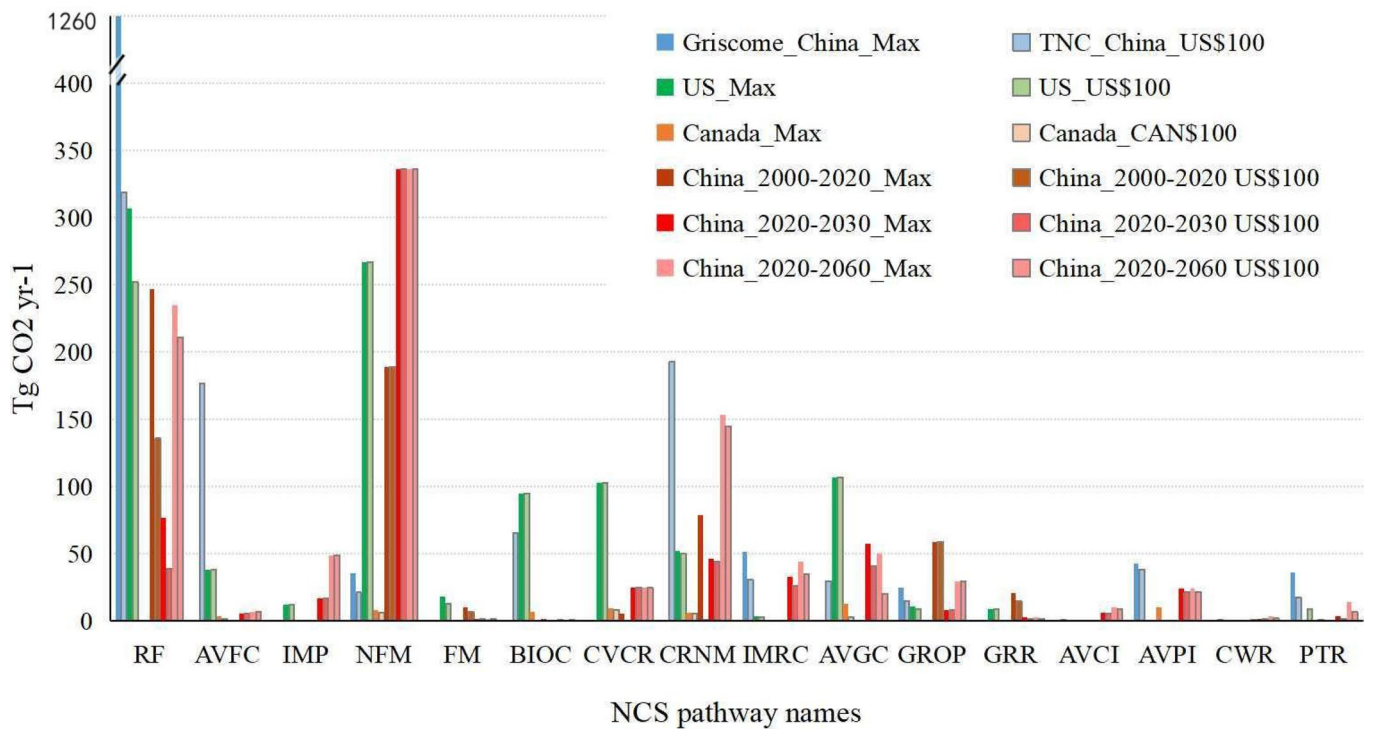
**Extended Data Fig. 4 | Data distribution of carbon density of tree layer with stand age (not including shrub, herb and floor layers).** The data points are collected from the literature, including 762 sites and 2363 plots. The blue bars represent the age distribution of sites. The fitting curve is based on linear generative additive model ( $r^2 = 0.30$ ,  $p < 0.001$ ).



**Extended Data Fig. 5 |** The burnt area by forest fire from 1949 to 2017. Data is obtained from <http://forest.ckcest.cn/zh/lytjsjfx.html>. Data is unavailable from 1991 to 1997.



**Extended Data Fig. 6 | N fertilizer use changes during 2000-2019.** Data is obtained from <http://www.stats.gov.cn/tjsj/ndsj/>.



**Extended Data Fig. 7 | Comparison of mitigation capacity between this study and previous studies (Griscome<sup>1</sup>, TNC<sup>27</sup>, US<sup>22</sup>, and Canada<sup>23</sup>).** Note that the estimates are maximum mitigation capacity or the amount of mitigation that can be achieved under US\$100 of mitigation price. The estimates of climate mitigation is at a 2030 reference year for global and Canada, and 2025 for the US.