

## Supplementary Information

### Exploring Negative Emission Potential of Biochar to Achieve Carbon Neutrality Goal in China

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## Supplementary Note 1 Available biomass feedstocks

### 1.1 Agricultural residues

The maximum theoretical potential represents the maximum amount of biomass feedstock available, assuming all biomass resources can be collected without competing uses. Theoretical agricultural residues ( $Theo\_Fd_{agri}$ , t/a) were calculated using formula (1-1), where  $Pro_k$  represents the production of crop  $k$  ( $k=1, 2, \dots, 16$ ) in 2018 (t/a),  $r_k$  represents the residue-to-product ratio of crop  $k$ , which is shown in Supplementary Table 1.

$$Theo\_Fd_{agri} = \sum_{k=1}^{16} Pro_k \cdot r_k \quad (1-1)$$

**Supplementary Table 1 Residue-to-product ratios of agricultural crops**

| Crops           | Residues                          | Liu & Shen,<br>2007 <sup>1</sup> | Bi et al.,<br>2009 <sup>2</sup> | Wang et al.,<br>2013 <sup>3</sup> | Cao et al.,<br>2018 <sup>4</sup> | Average |
|-----------------|-----------------------------------|----------------------------------|---------------------------------|-----------------------------------|----------------------------------|---------|
| Rice            | rice straw and                    | 1                                | 0.9                             | 1.04                              | 0.9                              | 0.96    |
|                 | rice hull                         |                                  | 0.27                            | 0.18                              |                                  | 0.23    |
| Wheat           | wheat straw                       | 1.1                              | 1.1                             | 1.28                              | 1.17                             | 1.16    |
| Maize           | maize straw                       | 2                                | 1.2                             | 0.93                              | 1.04                             | 1.29    |
|                 | maize cob                         |                                  | 0.25                            | 0.16                              |                                  | 0.21    |
| Other cereals   | straw to seed                     |                                  | 1.6                             | 2.32                              |                                  | 1.96    |
| Soybean         | soybean straw                     | 1.7                              | 1.6                             | 1.35                              | 1.6                              | 1.56    |
| Other beans     | straw to seed                     |                                  | 2                               |                                   |                                  | 2.00    |
| Tubers          | cirrus to tubers                  | 1                                | 0.5                             | 0.53                              | 0.57                             | 0.65    |
| Peanut          | peanut seedling and               | 1.5                              | 1.11                            | 1.26                              | 1.14                             | 1.25    |
|                 | husk                              |                                  |                                 |                                   |                                  |         |
| Rapeseed        | rapeseed straw                    | 3                                | 1.5                             | 2.9                               |                                  | 2.47    |
| Sesame seed     | sesame straw                      |                                  | 2.2                             | 1.89                              |                                  | 2.05    |
| Other oil crops | straw to seed                     | 2                                | 2.7                             | 2.63                              |                                  | 2.44    |
| Cotton          | cotton straw                      | 3                                | 9.2                             | 3.34                              | 3                                | 4.64    |
| Fiber           | fiber straw                       |                                  | 2.1                             | 1.73                              |                                  | 1.92    |
| Sugar cane      | sugarcane bagasse and             | 0.1                              | 0.3                             | 0.5                               | 0.3                              | 0.30    |
|                 | leaf tip                          |                                  |                                 |                                   |                                  |         |
| Sugar beet      | sugar beet bagasse, stem and leaf |                                  | 0.18                            | 0.42                              |                                  | 0.30    |
| Tobacco         | by-product                        |                                  | 1.6                             | 0.66                              |                                  | 1.13    |

The sustainable technical potential of available agricultural feedstocks ( $Sus\_Fd_{agri}$ , t/a) implies that 95% of agricultural residues can be collected due to the loss during harvesting, processing, and transportation<sup>5</sup>. Then, feedstocks for basic use (BU) need to be deducted. In China, approximately 144 Mt/a of straw was used for feed, raw materials, and substrates feed according to the latest data<sup>6</sup>. Therefore, BU was assumed to be 144Mt/a.

$$Sus\_Fd_{agri} = \sum_{k=1}^{16} Pro_k \cdot r_k \cdot 95\% - BU \quad (1-2)$$

The current technical potential of available agricultural feedstocks ( $Cur\_Fd_{agri}$ , t/a) represents the biomass resources available based on existing technologies and practices. According to current practice, the comprehensive utilization rate of straw in China is 88%, implying that at least 88% of crop residues can be collected currently<sup>6</sup>. Similarly, straw used for feed, raw materials, and substrates feed need to be deducted.

$$Cur\_Fd_{agri} = \sum_{k=1}^{16} Pro_k \cdot r_k \cdot 88\% \cdot BU \quad (1-3)$$

## 1.2 Forestry residues

With reference to Fu et al.<sup>7,8</sup>, 10 types of available forestry residues were considered: 1) wood residues: wood nursery residues, forest pruning residues including residues of woody fruits and other pruning residues, wood logging residues, wood bucking residues, wood handling residues, firewood, and waste wood; 2) bamboo residues: bamboo pruning residues and waste bamboo; and 3) herbaceous fruit tree residues.

Forestry residues were calculated using the residue ratio of each type of wood, woody fruits or bamboo, the frequency of harvesting or pruning, and the corresponding area. In terms of waste wood and bamboo, calculations were based on the density of the bamboo and wood, the recycling rate of the waste product, and the products over 10 years ago. Detailed formulas can be seen in the study of Fu et al.<sup>8</sup>. Data on planted areas and production were obtained from 2018 Chinese Agricultural Yearbook<sup>9</sup>, Forestry and Grassland Statistical Yearbook<sup>10</sup>, and Ninth National Forest Resources Inventory at the province level<sup>11</sup>. Other coefficients were retrieved from the study of Fu et al.<sup>12</sup>

As a result, the maximum theoretical potential of forestry residues in each province  $j$  ( $Theo\_Fd_{forest,j}$ , t/a) was calculated. The sustainable technical potential ( $Sus\_Fd_{forest,j}$ ) implies that 80% of forestry residues can be collected and utilized<sup>13</sup>. The current technical potential ( $Cur\_Fd_{forest,j}$ , t/a) implies that 28% of forestry residues can be utilized<sup>8</sup>.

Afterwards, available forestry residues were assigned to the  $0.5^\circ \times 0.5^\circ$  grid  $i$  based on land use type and gridded net primary productivity (NPP) in 2018.  $Fd_{forest,i}$  refers to the available forestry residues in each grid  $i$  (t/a),  $NPP_i$  refers to the NPP of ‘woodland and other wooded land’ in grid  $i$  (g/m<sup>2</sup>/a), and  $NPP_{ij}$  refers to the NPP of woodland and other wooded land in province  $j$  in which grid  $i$  is located (g/m<sup>2</sup>/a).

$$Fd_{forest,i} = Fd_{forest,j} \cdot \frac{NPP_i}{NPP_{ij}} \quad (1-4)$$

## 1.3 Grass residues

Total available grassland residues ( $Fd_{grass}$ , t/a) were calculated by using the statistical data as the total amount, and then were downscaled based on the NPP data as a weighting factor while excluding National Nature Reserve. First, according to the 2018 Annual Report on China's Forestry and Grassland Development<sup>14</sup>, total fresh grass production on natural grasslands nationwide was reported as 1,099 Mt, which was equivalent to approximately 339 Mt of dry grass. Second, dry grass was assigned to each grid according to the formula (1-5).  $NPP_i$  refers to the NPP of grassland on grid  $i$  (g/m<sup>2</sup>/a), and  $NPP_{grass}$  refers to the aggregated NPP of grassland.

Then, grassland residues in National Nature Reserves were excluded. Finally, 288 Mt of grassland residues are available, which is considered as the maximum theoretical potential.

$$Theo\_Fd_{grass\ i} = Fd_{statistic} \cdot \frac{NPP_i}{NPP_{grass}} \quad (1-5)$$

The sustainable technical potential of available grassland residues implies collectable grass that is not used as feed. It is worth noting that China's livestock industry is still primarily based on grazing other than mowing, indicating that grassland residues are not available for biochar production in regions where the theoretical carrying capacity of grasslands is lower than the actual livestock load. To estimate available grassland residues, firstly, the carrying capacity of natural grasslands in China in 2018 – 26,717.12 million sheep units - was adopted from 2018 Annual Report on China's Forestry and Grassland Development<sup>14</sup>. Then, the carrying capacity were downscaled based on the NPP data, resulting in capacity on each grid ( $loadcap_i$ , sheep unit).

Secondly, we calculated the actual livestock load ( $loadreal_i$ , sheep unit). We obtained end-of-year livestock population data for cattle, horses, and sheep from the China animal husbandry and veterinary yearbook at 2018 level<sup>15</sup> and downscaled the statistical data using the Gridded Livestock of the World (GLW 4) 2015 livestock spatial data<sup>16</sup>. Then, based on Specification for Calculation of Grassland Livestock Carrying Capacity and Grass Livestock Balance<sup>17</sup>, a yearly consumption of an adult sheep weighing 45 kg is 657 kg standard dry hay ( $Cons$ , t/sheep unit), and the conversion ratio of cattle (horse) to sheep is 5:1. Accordingly, we obtained the actual livestock load at the grid level. Finally, if the theoretical quantity was less than the actual quantity, the grassland residues available for biochar production were assumed to be zero. If the theoretical quantity exceeded the actual quantity, the difference was calculated as the available residue quantity, as shown in formula (1-6). It is worth noting that our calculations did not consider variations in utilization rates among different types of grasslands, potentially introducing bias to the results. Additionally, the utilization rate of grass for mowing might be higher, but we assumed that all grass for livestock comes from grazing, which might lead to underestimates.

$$Sus\_Fd_{grass\ i} = \max(0, loadcap_i - loadreal_i) \cdot Cons \quad (1-6)$$

## 1.4 Energy crops

Marginal land is considered crucial for the production of second-generation bioenergy crops, specifically for lignocellulosic biomass crops. Certain energy crops can thrive in harsh environmental conditions. For example, sweet sorghum stands out as a prominent non-food energy crop in China for bioenergy production, owing to its high biomass yield, tolerance to drought and cold, and other remarkable attributes. Miscanthus is a perennial C4 plant with efficient photosynthetic pathways. Switchgrass is a perennial grass species capable of producing high biomass while thriving in low-quality soils and enduring extreme climatic conditions. Based on existing literature regarding the definition of marginal land (as shown in the Supplementary Table 2), in the maximum theoretical potential scenario, we defined marginal land as shrubland, the intertidal zone, bottomland, and unused land. In the sustainable technical potential scenario, marginal land was defined as shrubland and unused land, where shrubland in National Special Provision Shrubland Counties is excluded<sup>18</sup>.

**Supplementary Table 2 The definition of marginal land and results comparison between existing research and this study**

| Study                            | Marginal land                                                                                                                                                      | Area (Mhm <sup>2</sup> )                 | Production                                             | Energy crops                                 |
|----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|--------------------------------------------------------|----------------------------------------------|
| this study                       | Shrub land, the intertidal zone, bottomland, and unused land including sandy, Gobi, saline, marshland, bare land, and bare rocky land.                             | 274.7                                    | 0.86 Gt/a                                              |                                              |
|                                  | After considering climate conditions                                                                                                                               | 53.8                                     |                                                        | Miscanthus                                   |
|                                  | Shrub land, and unused land including sandy, Gobi, saline, marshland, bare land, and bare rocky land, where the national special provision shrubland is excluded.  | 263.0                                    | 0.66 Gt/a                                              | Sweet sorghum<br>Switchgrass                 |
|                                  | After considering climate conditions and soil qualities                                                                                                            | 50.5                                     |                                                        |                                              |
| Zhang et al.,2020 <sup>19</sup>  | Sparse grassland, Shrub land, Sparse Forest land, Moderate coverage grassland, High coverage grassland, Saline-alkali land, Bottomland, Bare land, Intertidal zone | 184.9                                    | 1.76Gt/a<br>0.284Gt/a<br>9.7Mt/a                       | Miscanthus,<br>Switchgrass,<br>Jatropha seed |
| Nie et al., 2019 <sup>5,20</sup> | Tidal-flat land, sand land, saline-alkali soil land, swampland, bare land, etc.                                                                                    | 91.49–102.09                             | 12.30-20.46 EJ                                         | Sweet sorghum                                |
| Jiang et al.,2019 <sup>21</sup>  | Shrub land, sparse forest land, grassland, shoal/bottomland, alkaline land and bare land.                                                                          | 49.65                                    | 13.57Mt                                                | Sweet sorghum                                |
| Qin et al.,2018 <sup>22</sup>    | Alkaline land, bare land, degraded land, waste land, and idle land                                                                                                 | 3 - 100                                  |                                                        | Review                                       |
| Xue et al.,2016 <sup>23</sup>    | Sparse grassland, Shoal, Bottomland, Sand land, Gobi, Alkaline land, Wetland, Bare land, Bare rock                                                                 | 171.64(margin al land)<br>7.69(suitable) | 0.135Gt/a<br>183.9TWh/a<br>0.212GtCO <sub>2</sub> eq/a | Miscanthus                                   |

Total production of energy crops ( $Fd_e$ , t/a) was calculated by multiplying the area of marginal land ( $Area_m$ , 1 km × 1 km each) and the yield of the highest yielding crop types (i.e., miscanthus, switchgrass, or sweet sorghum) in each plot of land. Energy crops can only be planted in areas with suitable environmental conditions, including precipitation, temperature and slope (Supplementary Table 3, Supplementary Figure 1), of which the data sources are presented in Supplementary Table 5. The yield at the provincial level was adopted from previous studies (Supplementary Table 4), as shown in formulas (1-7) and (1-8).

$$Fd_e = \sum_m Area_m \cdot \max\{Yield\_mis_m, Yield\_swi_m, Yield\_swe_m\} \quad (1-7)$$

$$Yield_m = \begin{cases} Pt_m \cdot Yield_{province} & \text{inside regions with suitable environmental conditions} \\ 0 & \text{outside regions with suitable environmental conditions} \end{cases} \quad (1-8)$$

Besides, in terms of sustainable potential, since the soil quality would have influence on the growth potential of dedicated energy crops, we discounted the crop yield based on the soil quality data from Harmonized World Soil Database v1.2<sup>24</sup>, which includes seven evaluation dimensions

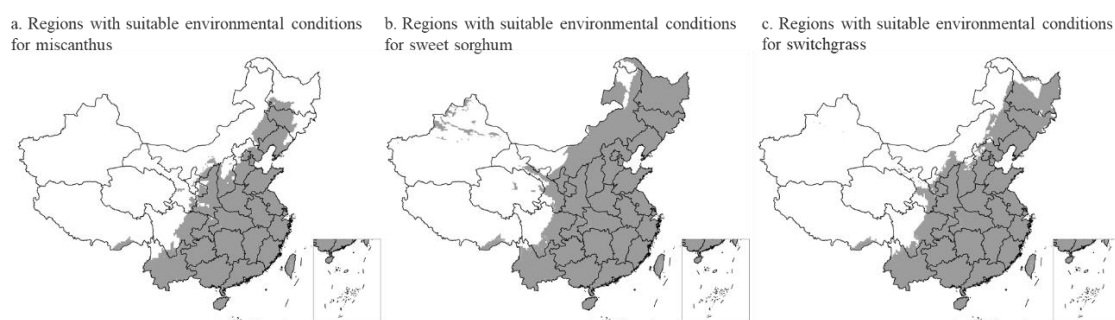
such as nutrient availability, with each dimension having 1-7 levels. The description of soil quality said ‘Only classes 1 to 4 are corresponding to an assessment of soil limitations for plant growth. Class 1 is generally rated between 80 and 100% of the growth potential, class 2 between 60 and 80%, class 3 between 40 and 60%, and class 4 less than 40%.’ Therefore, we took the yield data from existing literature as the optimal yield, took the grades with lowest level for each grid, and discounted the productivity ( $P_{tm}$ ) according to the description. The resulting energy crop planting area is 50.5 Mhm<sup>2</sup>, with a yield of 0.66 Gt/a, which is consistent with the range of existing estimates of 3-185 Mhm<sup>2</sup><sup>19,22,25</sup> and of 13.57 Mt/a to over 1 Gt/a<sup>19–21,23</sup>.

**Supplementary Table 3 Conditions suitable for miscanthus, switchgrass, and sweet sorghum**

| Crops         | Sources                          | AAT10 <sup>a</sup> | slope | precipitation |
|---------------|----------------------------------|--------------------|-------|---------------|
| Miscanthus    | Zhang et al., 2021 <sup>26</sup> | -                  | <25°  | -             |
|               | Yan et al., 2021 <sup>27</sup>   | > 3,200°C          | -     | >800mm        |
|               | Value adopted in this study      | > 3,200°C          | <25°  | >800mm        |
| Switchgrass   | Xue et al., 2016 <sup>23</sup>   | -                  | -     | >400 mm       |
|               | Zhang et al., 2021 <sup>26</sup> | -                  | -     | 381~762mm     |
|               | Yan et al., 2021 <sup>27</sup>   | > 2,500°C          | <25°  | >500 mm       |
|               | Value adopted in this study      | > 2,500°C          | <25   | >500 mm       |
| Sweet sorghum | Nie et al., 2019 <sup>20</sup>   | > 2,500°C          | <25°  | 200~1,500 mm  |
|               | Jiang et al., 2019 <sup>21</sup> | ≥ 2,000°C          | <25°  | >400 mm       |
|               | Value adopted in this study      | ≥ 2,000°C          | <25°  | >400 mm       |

Note: a. AAT10 = Active accumulated temperature ≥10 °C.

**Supplementary Figure 1 (a)–(c) Regions with environmental conditions suitable for the cultivation of energy crops.** The shapefile of national and provincial boundaries is quoted from the National Catalogue Service For Geographic Information, accessible at [www.webmap.cn](http://www.webmap.cn).



**Supplementary Table 4 Yields of miscanthus, switchgrass, and sweet sorghum at the provincial level**

| Crops                      | Sources                          | Year        | Model         |
|----------------------------|----------------------------------|-------------|---------------|
| Miscanthus                 | Zhang et al., 2020 <sup>19</sup> | 2017        | MiscanFor     |
| Switchgrass                | Zhang et al., 2017 <sup>28</sup> | 2017        | GEPIC         |
| Sweet sorghum <sup>a</sup> | Nie et al., 2019 <sup>20</sup>   | 2020        | AquaCrop      |
| DW t / (hm <sup>2</sup> a) | Miscanthus                       | Switchgrass | Sweet sorghum |
| Yunnan                     | 22.9                             | 8.9         | 14.7          |
| Guangxi                    | 23.5                             | 11.7        | 11.8          |

|                |      |      |      |
|----------------|------|------|------|
| Sichuan        | 13.2 | 8.2  | 14.9 |
| Guizhou        | 18.7 | 9.8  | 13.3 |
| Fujian         | 22.8 | 10   | 11.6 |
| Inner Mongolia | 6.6  |      | 13.6 |
| Hunan          | 19.7 | 10   | 12.3 |
| Shanxi         | 15.1 |      | 14.9 |
| Hubei          | 19   | 10.3 | 12.7 |
| Shaanxi        | 16.5 | 8.4  | 14.1 |
| Jiangxi        | 21.5 | 10.2 | 12.2 |
| Gansu          | 8.8  |      | 10.6 |
| Guangdong      | 25.3 | 10.6 | 11.4 |
| Heilongjiang   | 9.4  | 6.8  | 12.2 |
| Xinjiang       | 3.5  |      | 9.3  |
| Liaoning       | 15.5 | 7.2  | 13.9 |
| Chongqing      | 18.5 | 9.5  | 13.9 |
| Shandong       | 18.7 | 10.1 | 12.3 |
| Hebei          | 13.2 | 7.3  | 13.6 |
| Jilin          | 13.8 |      | 14.2 |
| Anhui          | 20.3 | 12.2 | 12.6 |
| Henan          | 18.1 |      | 10.9 |
| Qinghai        | 3.5  |      | 2.8  |
| Zhejiang       | 20.5 | 10   | 12.3 |
| Ningxia        | 10.5 |      | 13.5 |
| Hainan         | 26.6 |      | 10.9 |
| Jiangsu        | 19.3 | 12.5 | 12.7 |
| Beijing        | 16.4 |      | 14.1 |
| Tibet          | 4.1  |      | 4.5  |
| Tianjin        | 16.4 |      | 13.6 |
| Shanghai       |      |      | 12.7 |

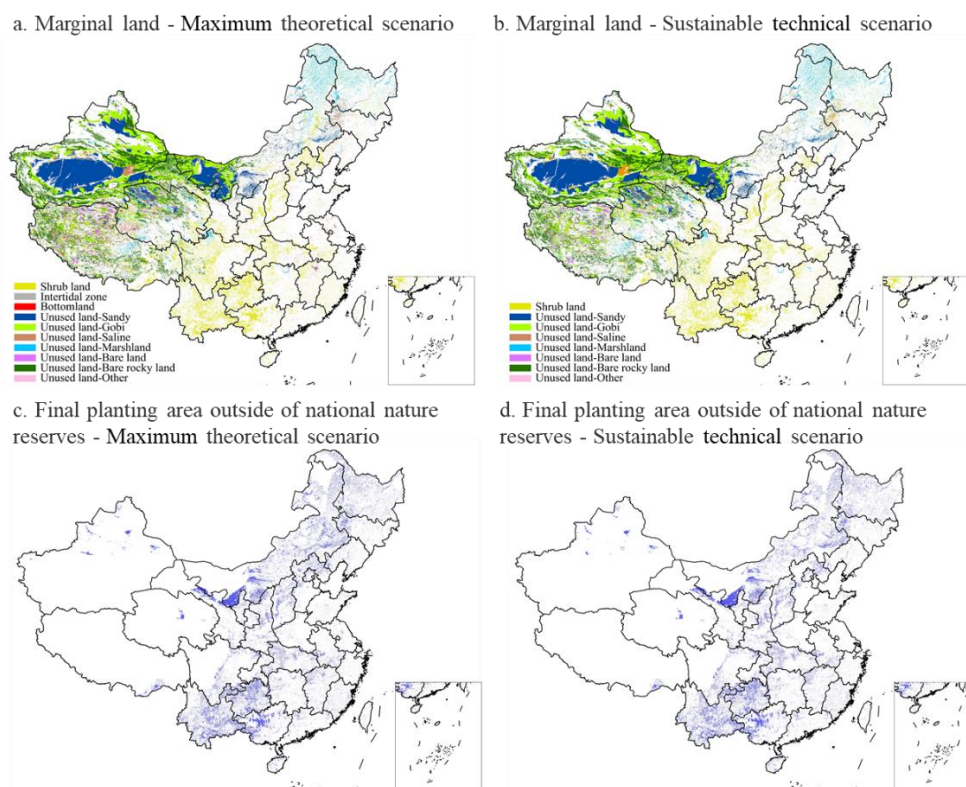
Note: a. Although sweet sorghum has high yield, apart from juice and sugar, only 50% of bagasse and pinnacles could be used for pyrolysis. 50% of the yields of sweet sorghum are presented in the table.

**Supplementary Table 5 Sources of land use and climate data**

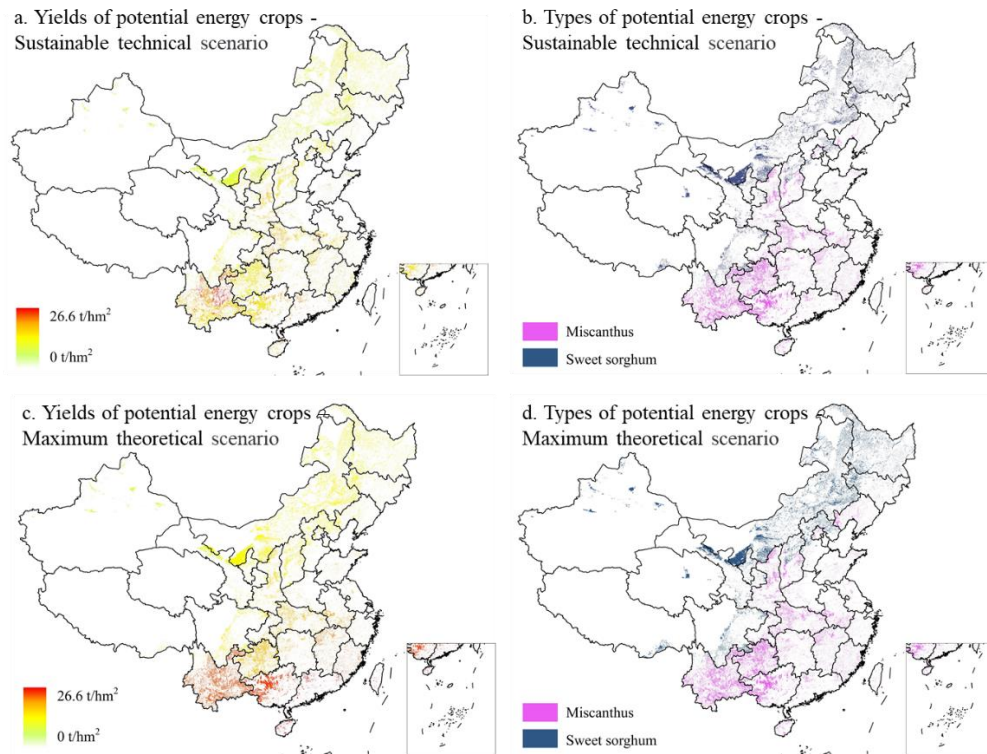
| Item                    | Resolution | Time period        | Data sources               |
|-------------------------|------------|--------------------|----------------------------|
| National Nature Reserve | Shape      | 2021 updated       | Yunnan University          |
| Land use                | 1 km       | 2018 retrieved     | CNLUCC, 2018 <sup>29</sup> |
| Temperature             | 27,830 m   | 2018-daily average | ERA5 <sup>30</sup>         |
| Precipitation           | 1/24°      | 2018 retrieved     | TerraClimate <sup>31</sup> |
| Slope                   | 90m        | 2000 retrieved     | SRTM data V4 <sup>32</sup> |

**Supplementary Figure 2 Marginal land and final planting area at the 1 km × 1 km level.** In maximum theoretical scenario, marginal land refers to shrub land, the intertidal zone, bottomland,

and unused land including sandy, Gobi, saline, marshland, bare land, and bare rocky land (a). In the sustainable technical scenario, marginal land refers to shrub land, and unused land including sandy, Gobi, saline, marshland, bare land, and bare rocky land, where the national special provision shrubland is excluded (b). The land use type data are filtered from China's multi-period land use land cover remote sensing monitoring dataset<sup>29</sup>. Considering the climate constrains and nature reserves, final planting areas are shown in (c) and (d). The shapefile of national and provincial boundaries is quoted from the National Catalogue Service For Geographic Information, accessible at [www.webmap.cn](http://www.webmap.cn).

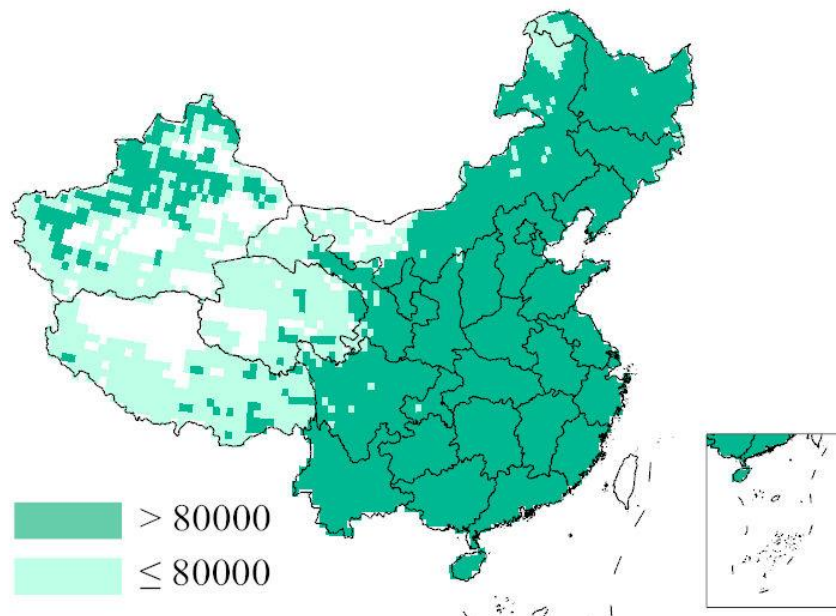


**Supplementary Figure 3 (a, c) Yields and (b, d) types of potential energy crops on marginal land at the 1 km × 1 km level after best technology selection of sweet sorghum, switchgrass, and miscanthus.** Note that switchgrass was not selected because of its relatively low yield. Although sweet sorghum has high yield, apart from juice and sugar, only 50% of bagasse and pinnacles could be used for pyrolysis. The shapefile of national and provincial boundaries is quoted from the National Catalogue Service For Geographic Information, accessible at [www.webmap.cn](http://www.webmap.cn).

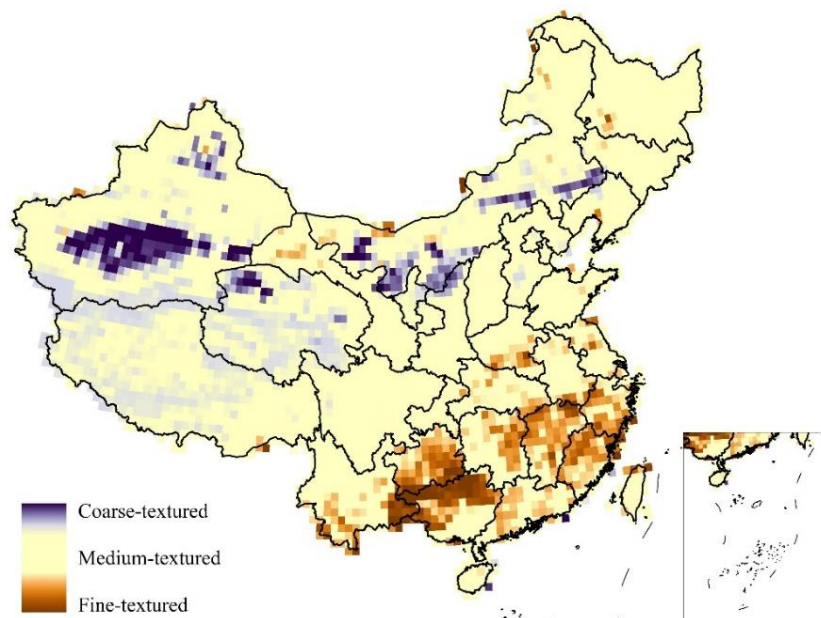


## 1.5 Biomass abundance and soil texture

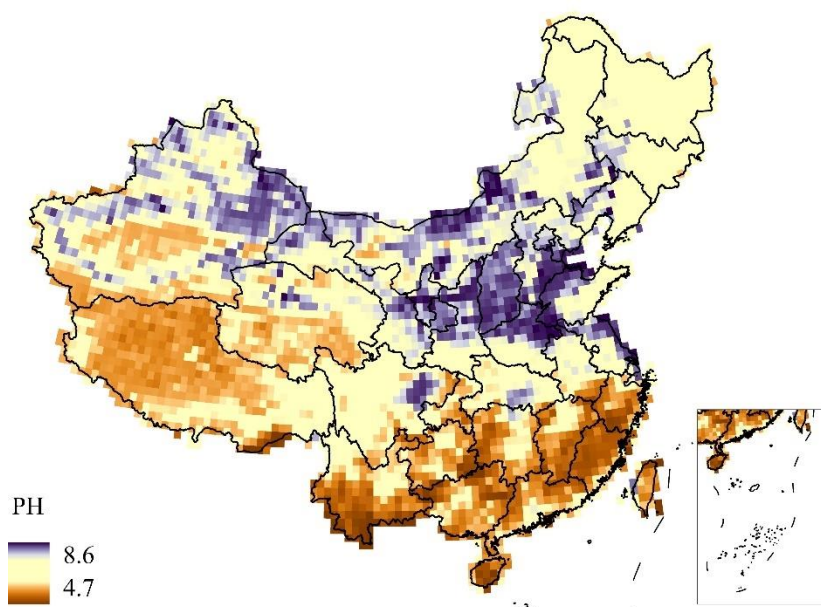
**Supplementary Figure 4 Biomass abundance.** Notably, biomass abundance needs to achieve a lower limit, otherwise it will not only be difficult to harvest and transport, but also the investment might be uneconomic. According to our calculations, more than 80% of grids had more than 80,000 t of feedstock available. We set a lower limit of 80,000 t of feedstock in each 0.5° grid. If the feedstock of the grid was <80,000 t, the investment cost would be increased (by no more than 20%). Grids with low feedstock are mainly distributed in Southwest and Northwest China. The shapefile of national and provincial boundaries is quoted from the National Catalogue Service For Geographic Information, accessible at [www.webmap.cn](http://www.webmap.cn).



**Supplementary Figure 5 Soil texture on a  $0.5^\circ \times 0.5^\circ$  grid.** Resampling the data obtained from Harmonized World Soil Database (HWSD) <sup>24</sup>. Medium-textured soil consists of 6-silt, 7-silt loam, 8-sandy clay, 9-loam, and 10-sandy clay loam. Coarse-textured soil consists of 11-sandy loam, 12-loamy sand, and 13-sand. Fine-textured soil consists of 1-clays (heavy), 2-silty clay, 3-clay, 4-silty clay loam, and 5-clay loam. The shapefile of national and provincial boundaries is quoted from the National Catalogue Service For Geographic Information, accessible at [www.webmap.cn](http://www.webmap.cn).



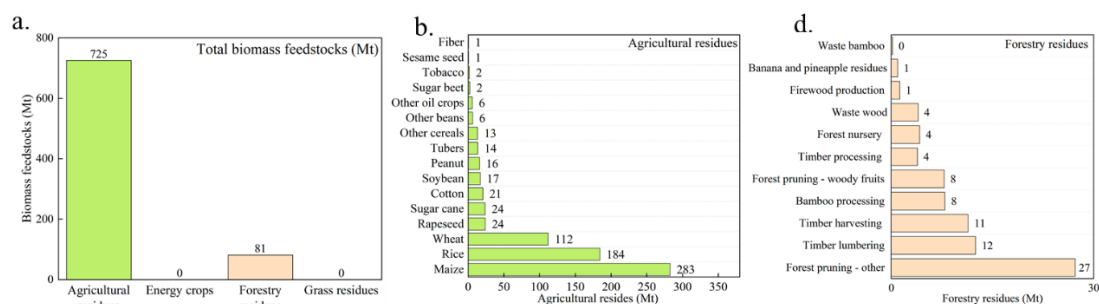
**Supplementary Figure 6 PH on a  $0.5^\circ \times 0.5^\circ$  grid.** Resampling the data obtained from Harmonized World Soil Database (HWSD) <sup>24</sup>. The shapefile of national and provincial boundaries is quoted from the National Catalogue Service For Geographic Information, accessible at [www.webmap.cn](http://www.webmap.cn).



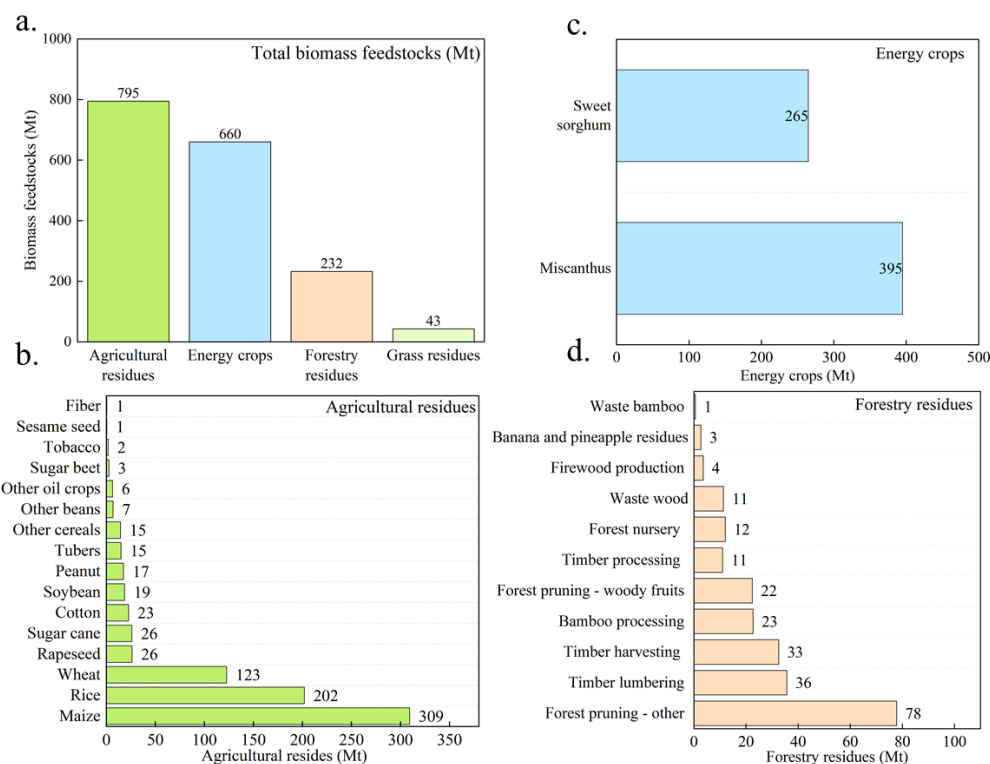
## 1.6 Available biomass feedstocks

**Supplementary Figure 7 Types of biomass feedstock available for biochar production under the current technical scenario (in dry weight).** a) Total biomass feedstock, including agricultural

residues and forestry residues. b) Agricultural residues that consist of 16 types of residues. c) Forestry residues that consist of 10 types of residues. Note that ‘forest pruning – other’ and ‘forest pruning – woody fruits’ both belong to forest pruning.

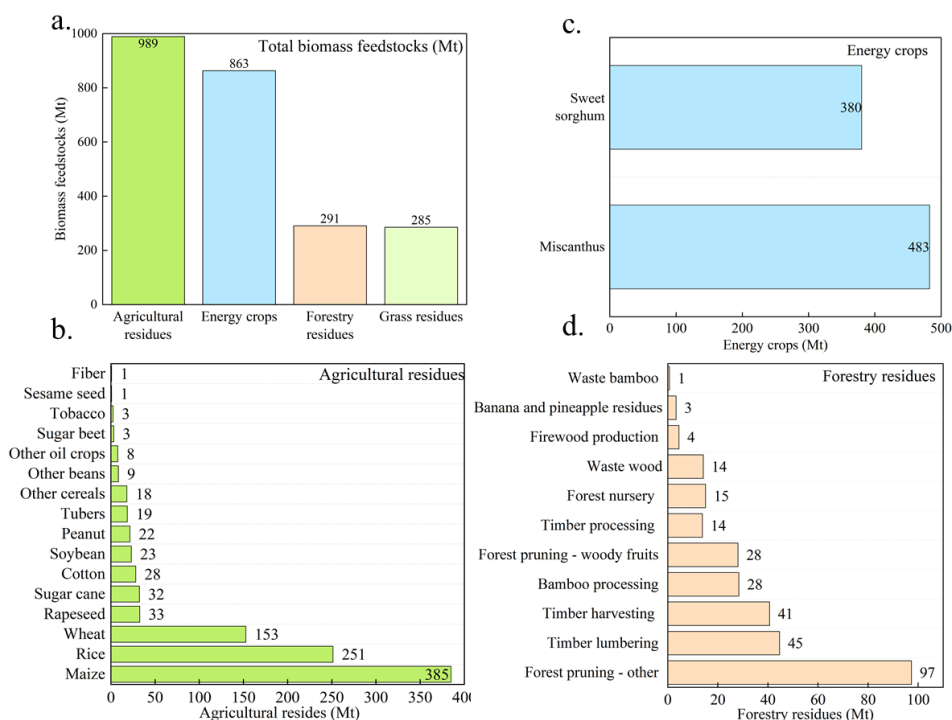


**Supplementary Figure 8 Types of biomass feedstock available for biochar production under the sustainable scenario (in dry weight).** a) Total biomass feedstock, including agricultural residues, energy crops, forestry residues, and grass residues. b) Energy crops that consist of sweet sorghum and miscanthus. Note that switchgrass is not listed owing to its low yield. c) Agricultural residues that consist of 16 types of residues. d) Forestry residues that consist of 10 types of residues. Note that ‘forest pruning - other’ and ‘forest pruning - woody fruits’ both belong to forest pruning.



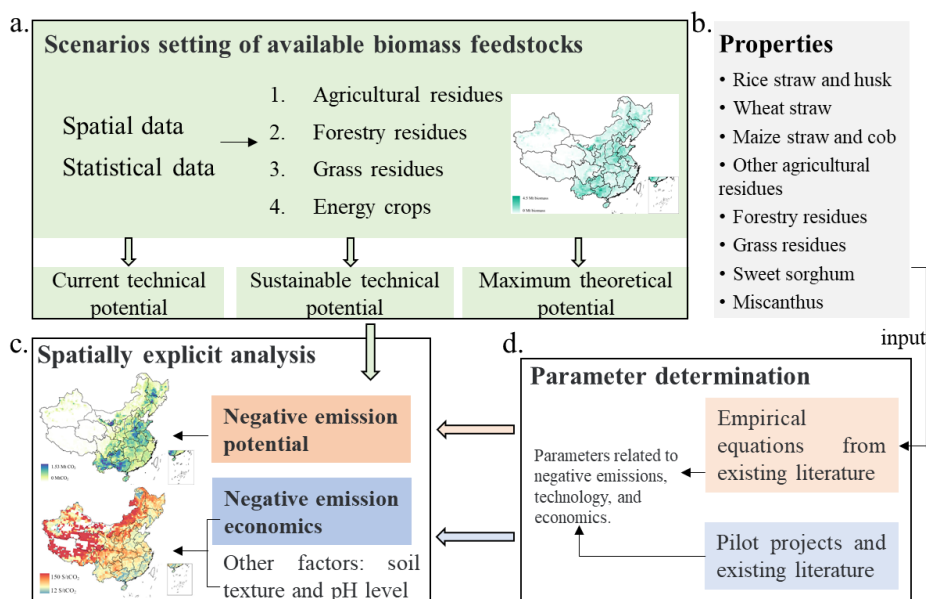
**Supplementary Figure 9 Types of biomass feedstock available for biochar production under the maximum theoretical scenario (in dry weight).** a) Total biomass feedstock, including agricultural residues, energy crops, forestry residues, and grass residues. b) Energy crops that consist of sweet sorghum and miscanthus. Note that switchgrass is not listed owing to its low yield. c) Agricultural residues that consist of 16 types of residues. d) Forestry residues that consist of 10

types of residues. Note that ‘forest pruning – other’ and ‘forest pruning – woody fruits’ both belong to forest pruning.



## Supplementary Note 2 Slow pyrolysis

**Supplementary Figure 10 Framework for Biochar Potential and Economics Evaluation.** a) Scenarios setting of available biomass feedstocks. b) Properties of various types of biomass feedstocks, which serve as inputs for the empirical equations. c) Spatially explicit analysis of negative emission potential and economics of biochar. d) Determination of key parameters related to negative emissions, technology, and economics. The shapefile of national and provincial boundaries is quoted from the National Catalogue Service For Geographic Information, accessible at [www.webmap.cn](http://www.webmap.cn).



The outputs of slow pyrolysis vary considerably depending on biochar type and pyrolysis conditions such as temperature. To make a comprehensive assessment, it is not likely to directly adopt values from a single pilot project or experiment because existing pilot projects typically use only one or two types of biomass feedstock, and laboratory experiments on the properties of biochar often preclude studies of by-products.

We thus made efforts to process data from existing experiments or pilot projects with the aim of evaluating the negative emissions and economics of biochar produced from various biomass types, while maintaining conditions that were as consistent as possible. We tried to get comparable biochar parameters within a unified framework. Notably, the purpose of this data processing procedure was not to develop an accurate model of slow pyrolysis, but to make the outputs reported in the literature comparable. The steps were as follows.

First, we differentiated the weight conversion rate ( $\alpha_i^{DAF}$ ) and carbon content ( $\beta_i^{DAF}$ ) of dry ash-free (DAF) biochar according to the GHG accounting framework of biochar application developed by Woolf et al.<sup>33</sup>. This framework is grounded in a comprehensive analysis of current empirical data. At the given temperature ( $T$ ), the weight conversion rate of biochar<sup>34</sup> and carbon content<sup>35</sup> can be calculated with the input being the ash content of biochar ( $Bc\_ash_i$ ) and lignin content of biomass feedstocks ( $L_i$ ). Then, we calculated the weight conversion rate ( $\alpha_i$ ) and the carbon content of resultant biochar ( $\beta_i$ ). The formulas are shown as follows:

$$\beta_i = \beta_i^{DAF} \cdot (1 - Bc\_ash_i) \quad (2-1)$$

$$\beta_i^{DAF} = 0.93 - 0.92 \cdot e^{-0.0042 \cdot T} \quad (2-2)$$

$$Bc\_ash_i = Bm\_ash_i / \alpha_i \quad (2-3)$$

$$\alpha_i = \alpha_i^{DAF} + Bm\_ash_i \quad (2-4)$$

$$\alpha_i^{DAF} = 0.1261 + 0.5391 \cdot e^{-0.004 \cdot T} + 0.2733 \cdot L_i \quad (2-5)$$

The data of  $Bm\_ash_i$  and  $L_i$  in term of the residues of main crops in China - rice husk, rice straw, wheat, maize straw, maize cob - were adopted from chemical composition analysis studies<sup>36,37</sup>, which either research on typical Chinese varieties or averaged over multiple crop composition results. The data of  $Bm\_ash_i$  and  $L_i$  of the grass residues and forestry residues were adopted from Woolf et al.<sup>33</sup>, and those of miscanthus and sweet sorghum were adopted from Brosse et al.<sup>38</sup> and Lu et al.<sup>39</sup>. After calculation,  $\alpha_i$  and  $\beta_i$  were shown in Supplementary Table 6.

**Supplementary Table 6 Carbon contents and weight conversion rates of biochar produced from various feedstocks.**

| Data             | Rice  |       | Wheat | Maize |       | Other agricultural residues | Grass residues | Forestry residues | Energy crops |               |
|------------------|-------|-------|-------|-------|-------|-----------------------------|----------------|-------------------|--------------|---------------|
|                  | Straw | Husk  |       | Straw | Cob   |                             |                |                   | miscanthus   | Sweet sorghum |
| $\alpha_i^{DAF}$ | 22.8% | 25.2% | 21.5% | 22.3% | 22.9% | 23.4%                       | 21.8%          | 25.3%             | 21.9%        | 24.2%         |
| $\alpha_i$       | 36.2% | 42.9% | 28.6% | 28.6% | 26.8% | 29.2%                       | 28.8%          | 27.5%             | 24.6%        | 25.0%         |
| $\beta_i$        | 52.9% | 49.3% | 63.0% | 65.2% | 71.9% | 67.2%                       | 63.5%          | 77.2%             | 74.7%        | 81.0%         |
| $Bm\_ash_i$      | 13.4% | 17.7% | 7.1%  | 6.4%  | 3.8%  | 5.8%                        | 7.0%           | 2.2%              | 2.7%         | 0.9%          |
| $L_i$            | 15.6% | 24.3% | 10.7% | 13.5% | 15.9% | 17.7%                       | 11.8%          | 24.7%             | 12.3%        | 20.4%         |

Furthermore, to determine the high heating value ( $HHV_i$ ) of biochar, we adopted empirical correlations based on proximate analysis that are developed by Qian et al.<sup>40</sup>. They selected ten kinds representative biomass to prepare biochar materials, and the correlation has been verified by experimental data and has generalizability.

$$HHV_i = -30.3\beta_i^2 + 65.2Bc\_ash_i + 55.4\beta_i - 48.5Bc\_ash_i + 9.591 \quad (2-6)$$

Low heating value ( $LHV_i$ ) of biochar is the heat of combustion reduced by the heat of water evaporation, which is calculated according to equation from US Environmental Protection Agency, as shown in formula (2-7), where  $W$  is weight percent of moisture, and  $H_i$  is weight percent of hydrogen. Then, using formula from Woolf et al.<sup>34</sup>, hydrogen content of biochar can be calculated based on temperature, as shown in formula (2-8) and (2-9). Here, we simplified the calculation by assuming that  $W$  is 0.

$$LHV_i = HHV_i - 10.55(W + 9H_i) \quad (2-7)$$

$$H^{DAF} = -0.0041 + 0.1 \cdot e^{-0.0024 \cdot T} \quad (2-8)$$

$$H_i = H^{DAF} \cdot (1 - Bc\_ash_i) \quad (2-9)$$

Then,  $LHV_i$  were calculated and shown in Supplementary Table 9.

Besides biochar, there are also by-products generated during the process of biomass pyrolysis. There are various technologies for biochar production, including carbonization, dry distillation, and gasification with multiple co-production techniques. The by-products may include syngas, bio-oil, wood vinegar, electricity, and others. Correspondingly, the energy efficiency varies significantly depending on the specific technology and process conditions.

To ensure that the identified technology type and the benefits from by-products align closely with reality in China, we both conducted literature research and obtained first-hand data from biochar production facilities, which aimed at facilitating a more accurate and reasonable economic evaluation.

Firstly, we selected the technology of biomass gasification for syngas and biochar co-production. Despite having a relatively lower weight conversion rate of biochar compared to other technologies, it has demonstrated significant economic benefits from both biochar and syngas, and is considered one of the key industrialization directions for biochar production in China. Domestic research teams, including Nanjing Agricultural University, Chinese Academy of Agricultural Engineering (Ministry of Agriculture), and Huazhong University of Science and Technology, have been actively involved in this field and performed a series of experiments, as shown in Supplementary Table 8, based on which, we have determined the energy efficiency, with a median value of 71% ( $\mu$ , %).

Secondly, our survey on existing biochar pilot projects also supports the feasibility and development potential of biomass gasification for co-production technology, as shown in Supplementary Table 9. According to the practical data, we identified the types of by-products and their benefits. Given that in biomass gasification technology, gaseous tar and other products were almost combusted to powering the process, by-product benefits solely come from remaining usable syngas. Syngas has some main uses: for self-use to save heating expenses and conversion

into industrial steam or electricity. Here, syngas was assumed to be converted into industrial steam, as some of the pilot projects did (Supplementary Table 9). The heat value of medium-temperature and medium-pressure steam commonly used in industries at 400°C and 4 MPa is approximately 3.278 GJ/t, with a price of 250 RMB per ton. The energy efficiency from syngas to steam is 92%. In this way, the benefits of syngas can be calculated.

Finally, to ensure energy balance, the energy preserved in syngas ( $Pro\_gas_i$ , GJ/t biomass) was calculated by subtracting the energy preserved in the biochar from the total preserved energy in biomass and additional energy input ( $Ade_i$ , kWh/t biomass), as shown in formula (2-10). The system requires a few additional energy consumptions to sustain the operation, which is assumed to be 90 kWh/t biomass according to pilot projects (Supplementary Table 9). As a result, the benefits of the by-products and the production of various types of biochar would be differentiated. The data and data sources used are listed in Supplementary Table 7.

$$Pro\_gas_i = (Ade_i - 0.0036 \text{ GJ/kWh} + Bio\_LHV_i) \cdot \mu - Bc\_LHV_i \cdot \alpha_i \quad (2-10)$$

**Supplementary Table 7 Low heating value of biochar and biomass and energy preserved in syngas.**

| Parameters diverse in feedstocks |                                     | Sources                                                                      |
|----------------------------------|-------------------------------------|------------------------------------------------------------------------------|
| $Bc\_LHV_i$                      | low heating value of biochar (GJ/t) | Calculated based on proximate formula                                        |
| $Bio\_LHV_i$                     | low heating value of biomass (GJ/t) | Renewable Energy 2015 (China) <sup>41</sup>                                  |
| $Pro\_gas_i$                     | production of syngas (GJ/t biomass) | Calculated based on $LHV_i$ of biochar, energy efficiency of pyrosis process |

| Data         | Rice  |      | Wheat |       | Maize |         | Other agricultural residues | Grass residues | Forestry residues | Energy crops |               |
|--------------|-------|------|-------|-------|-------|---------|-----------------------------|----------------|-------------------|--------------|---------------|
|              | Straw | Husk | straw | Straw | Cob   |         |                             |                |                   | miscanthus   | Sweet sorghum |
| $Bc\_LHV_i$  | 20.0  | 19.4 | 22.8  | 23.6  | 26.3  | 24.4    |                             | 23.0           | 28.9              | 27.6         | 30.9          |
| $Bio\_LHV_i$ | 13.8  | 13.7 | 14.6  | 15.5  | 16.2  | diverse |                             | 17.5           | 14.6              | 17.5         | 17.5          |
| $Pro\_gas_i$ | 2.79  | 1.64 | 4.09  | 4.47  | 4.71  | diverse |                             | 6.03           | 2.68              | 5.85         | 4.92          |

**Supplementary Table 8 Parameters of biomass gasification for syngas and biochar co-production technology.**

| No.                     | 1                                                                             | 2                                                                   |                                              | 3                                                                   | 4                                                                                                       | 5                                                                                                       | 6                                                                                                      |                              |                             | 7                                                                           | 8                                                                                |
|-------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------------|----------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|------------------------------|-----------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Technology Type         | Fluidized bed gasification for co-generation of electricity, biochar and heat | Downdraft fixed bed biomass multi-production gasifier               |                                              | Downdraft fixed bed biomass multi-production gasifier               | Biomass Continuous Grading Pyrolysis                                                                    | Carbon, gas and oil poly-generation pilot system                                                        | Straw carbonization polygeneration system                                                              |                              |                             | Mobile Equipment of Corn Stalk In-situ Returning Carbonization              | Biomass intermediate pyrolysis poly-generation (BIPP) system                     |
| Team                    | Zhang et al., 2015 <sup>42</sup><br>Nanjing Agricultural University           | Cheng et al., 2015 <sup>43</sup><br>Nanjing Agricultural University |                                              | Zhang et al., 2021 <sup>44</sup><br>Nanjing Agricultural University | Zhao et al., 2016 <sup>45</sup><br>Chinese Academy of Agricultural Engineering, Ministry of Agriculture | Cong et al., 2017 <sup>46</sup><br>Chinese Academy of Agricultural Engineering, Ministry of Agriculture | Huo et al., 2017 <sup>47</sup><br>Chinese Academy of Agricultural Engineering, Ministry of Agriculture |                              |                             | Zhao et al., 2023 <sup>48</sup><br>Chinese Academy of Agricultural Sciences | Yang et al., 2021 <sup>49</sup><br>Huazhong University of Science and Technology |
| Biomass Type            | straw                                                                         | furfural residues 20.87 MJ/kg                                       | wasted mushroom inoculation bags 18.01 MJ/kg | apricot shell                                                       | corn stalk 16.82 MJ/kg                                                                                  | peanut husk                                                                                             | straw                                                                                                  |                              |                             | corn stalk 15.19 MJ/kg<br>50 kg /h                                          | 14.7GJ/t                                                                         |
| Temperature             | 600 ~ 800°C                                                                   | 600 ~ 800°C                                                         | 400 ~ 600°C                                  |                                                                     | 550-600°C                                                                                               |                                                                                                         | 450 ~ 500°C                                                                                            | 450 ~ 500°C                  | 450 ~ 500°C                 | 600 ~ 800°C                                                                 | 550°C                                                                            |
| Biochar Yield           | 15%-25%                                                                       | 30.0%                                                               | 22.3%                                        | 25.9%                                                               | 29.97%                                                                                                  | 31.3%                                                                                                   | 260 ~ 300kg /t                                                                                         | 280 ~ 320kg /t               | 280 ~ 320kg /t              | 21.0%                                                                       | 7.09GJ/t biomass                                                                 |
| Biochar Calorific Value |                                                                               | 26.18 MJ/kg                                                         | 20.09 MJ/kg                                  |                                                                     | 26.21 MJ/kg                                                                                             |                                                                                                         | 20 ~ 23 MJ/kg                                                                                          | 25 ~ 30 MJ/kg                | 25 ~ 30 MJ/kg               | 22 MJ/kg                                                                    | 25.68                                                                            |
| Syngas Yield            | 1.7-2.3m <sup>3</sup> /kg                                                     | 2.49 m <sup>3</sup> /kg                                             | 2.25 m <sup>3</sup> /kg                      | 1.87kg/kg                                                           | 0.20m <sup>3</sup> /kg                                                                                  | 0.28m <sup>3</sup> /kg                                                                                  | 400m <sup>3</sup> /t                                                                                   | 350m <sup>3</sup> /t         | 300m <sup>3</sup> /t        |                                                                             | 0.75GJ/t biomass                                                                 |
| Syngas Calorific Value  | 1100-1200kcal/ Nm <sup>3</sup>                                                | 4.86 MJ/m <sup>3</sup>                                              | 4.92 MJ/m <sup>3</sup>                       | 1100~1300kcal/m <sup>3</sup>                                        |                                                                                                         | 16.3MJ/m <sup>3</sup>                                                                                   | 3 ~ 6(MJ/ Nm <sup>3</sup> )                                                                            | 10~12 (MJ/N m <sup>3</sup> ) | 8~10( MJ/N m <sup>3</sup> ) | 346 MJ/h                                                                    | 284.2                                                                            |
| Bio-oil Yield           | Gaseous tar is fed into the combustor for use in a                            |                                                                     |                                              |                                                                     | 2.44%                                                                                                   | 3.40%                                                                                                   | Small quantity, not intend                                                                             | -                            | 280 ~ 300kg /t biomass,     |                                                                             | 2.13GJ/t biomass                                                                 |

|                                       |                                                                                                                                                    |  |  |                                                                                                                                                                  |                                                         |                 |                        |                  |                         |                       |                 |
|---------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|--|--|------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|-----------------|------------------------|------------------|-------------------------|-----------------------|-----------------|
| Bio-oil Calorific Value               | gas-fired boiler, generating medium-temperature and medium-pressure steam to drive a steam turbine for power generation while also providing heat. |  |  |                                                                                                                                                                  |                                                         |                 | ed for production      | -                | 5.9 MJ·kg <sup>-1</sup> |                       |                 |
| Additional Energy Input for Equipment |                                                                                                                                                    |  |  | 17.71% accounts for heat loss, providing the heat required for activation reactions and the heat loss during the cooling process in the dry purification process | External heating with resistance wire 1.5kWh/kg biochar | Bio-oil, syngas | Spontaneous combustion | External heating | External heating        | 9MJ/h 10 kg biochar/h | 14.7GJ/         |
| Energy Efficiency                     | >80%                                                                                                                                               |  |  | 82%                                                                                                                                                              | 53%                                                     | 68%             | 52%                    | 73%              | 80%                     | 74. 6%                | 48.75% - 73.69% |

2

Supplementary Table 9 Parameters of Pyrolysis Plants from Surveys

| No.                        | 1                                                                      | 2                                                               | 3                                                                           | 4                                          | 5                                                                    | 6                                                                 |
|----------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------------------|--------------------------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------|
| Location                   | Shenyang                                                               | Inner Mongolia                                                  | Heilongjiang                                                                | Henan                                      | Anhui                                                                | Guizhou                                                           |
| Commencement of Operation  | 2014                                                                   | 2021                                                            | 2018                                                                        | 2016                                       | 2019                                                                 | 2018                                                              |
| Pyrolysis Technology       | Fixed-bed biomass carbonization equipment, and co-production of syngas | Fixed-bed straw gasification, and co-production of biochar      | Continuous anaerobic carbonization, and co-production of syngas and bio-oil | Gasification, and co-production of biochar | Gasification, and gas supply for 30t boiler co-production of biochar | Self-heating low-temperature pyrolysis                            |
| Biomass Type               | Corn stalks, rice husks                                                | Sunflower stalks                                                | Corn stalks, hemp stalks                                                    | Peanut shells                              | Wood/chips, rice husk, Wood/chips                                    | Tobacco stems, tobacco stalks, tobacco leaves, pine needles, etc. |
| Additional energy input    | 10kWh/t biomass                                                        | 90kWh/t biomass                                                 | 35kWh/t biomass                                                             | Liquefied gas ignition on start-up only    | Diesel ignition on start-up only                                     | 22kWh/t biomass                                                   |
| Biochar Yield              | 1/5-1/4                                                                | 1/5 Sunflower stalks<br>1/3 Maize cob                           | 1/4                                                                         | 1/4                                        | Rice husk 30%<br>Straw23%<br>Wood/chips 17%                          | 1/3                                                               |
| Bio-oil Yield and Quantity | -                                                                      | -                                                               | Utilized as raw material for asphalt, priced at 2000 RMB per ton.           | -                                          | -                                                                    | -                                                                 |
| Syngas Yield               | Nodata                                                                 | 100*10 <sup>6</sup> m <sup>2</sup> /a<br>3100KJ/Nm <sup>3</sup> | Nodata                                                                      | Nodata                                     | 210000 t/a                                                           | Nodata                                                            |

|                    |                                                               |                                                                         |                                                         |                                         |                                               |                                                                                                                                   |
|--------------------|---------------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------|-----------------------------------------|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| Syngas Utilization | For self-use, saving 100000 yuan per year on heating expenses | For self-use, drying products and providing heating in the factory area | For self-use, utilizing excess heat in the factory area | For self-use, using a rotary kiln dryer | Conversion to industrial steam at 250 RMB/ton | Continuing as a heat source for the pyrolysis equipment and converting excess heat to industrial saturated steam at 200 yuan/ton. |
| Other By-products  | Nodata                                                        | For self-use, wood vinegar.                                             | Nodata                                                  | For self-use, wood vinegar.             | Nodata                                        | Nodata                                                                                                                            |

### Supplementary Note 3 Negative emission potential of biochar

CO<sub>2</sub> fixed in one unit of feedstock from the atmosphere by photosynthesis, then transferred and permanently preserved in biochar  $Seq_i$  (tCO<sub>2</sub>/t biomass) can be calculated using the coefficients of  $\alpha_i$  - weight conversion rate from feedstock  $i$  to biochar (%),  $\beta_i$  - carbon content of biochar produced by feedstock  $i$  (%), and  $per$  - the permanence rate of biochar over 100 years (%), as shown in formula (3-1).  $per$  (%) was calculated as 75.08%, based on the formula from Woolf et al.<sup>33</sup>, as presented in formula (3-2) below, where  $T$  is the pyrolysis temperature (550°C in this study).

$$Seq_i = \alpha_i \cdot \beta_i \cdot \frac{44}{12} \cdot per \quad (3-1)$$

$$per = 0.28 + 8.56 \cdot 0.0001 \cdot T \quad (3-2)$$

The total negative emission potential of biochar ( $NE$ , tCO<sub>2</sub>) was then calculated from  $Seq_i$  and  $Res_i$  (t biomass) - available feedstock biomass  $i$ , which includes various agricultural residues, grass residues, forestry residues, and potential energy crops:

$$NE = \sum_i Seq_i \cdot Res_i \quad (3-3)$$

### Supplementary Note 4 Effects of biochar application on soil

#### 4.1 Avoided soil greenhouse gas (GHG) emissions

The effects of avoidance of soil GHG emissions were calculated, assuming that biochar was returned to the locations from which the feedstocks were harvested. First, the optimal application rate  $\gamma$  was determined based on existing meta-analysis. Second, the avoided soil GHG emissions at an optimal biochar application rate were determined based on meta-analysis. Then, the actual biochar production was calculated from the feedstocks  $Res_i$  and weight conversion rate  $\alpha_i$ . Finally, the total avoided soil GHG emissions ( $ASGHG$ , CO<sub>2</sub>eq/a) were estimated by multiplying the actual biochar production by the effects of soil GHG emissions avoidance apportioned to one unit of biochar, as shown in formula (4-1):

$$ASGHG = \sum_i (Res_i \cdot \alpha_i \cdot \sum_j (f_{ij} \cdot E_j \cdot GWP100_j) \cdot \frac{1}{\gamma}) \quad (4-1)$$

where  $j$  represents soil CH<sub>4</sub>, N<sub>2</sub>O, and CO<sub>2</sub>;  $f_{ij}$  is the rate of decrease in soil GHG emissions  $j$  after biochar application (%), which was adopted from meta-analysis and the diverse feedstocks  $i$ , as shown in Supplementary Table 10;  $E_j$  is the original soil emissions (t/ha/a). Here,  $GWP100_{CH_4}$  was adopted as 28 and  $GWP100_{N_2O}$  was adopted as 265.

**Supplementary Table 10 Data and data sources related to soil GHGs**

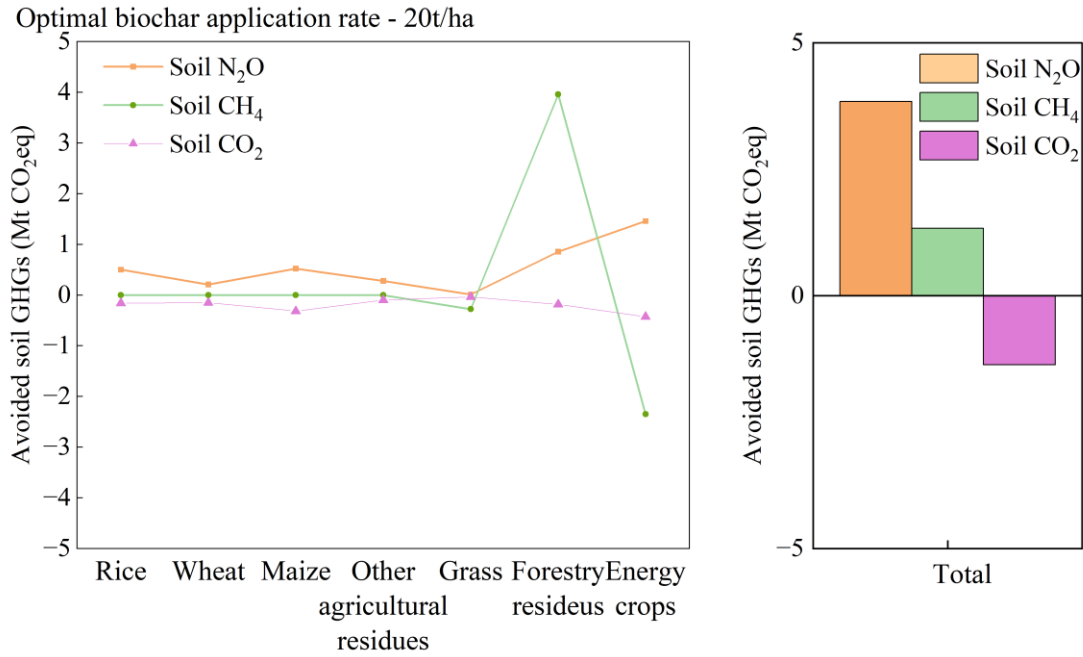
| Parameters diverse in feedstocks |                                                                              | Sources                                                                         |
|----------------------------------|------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| $f_{CH_4}$                       | decreasing rate of soil CH <sub>4</sub> emissions (%)                        | Meta-analysis:                                                                  |
| $f_{N_2O}$                       | decreasing rate of soil N <sub>2</sub> O emissions (%)                       | He et al., 2017 <sup>50</sup> ; Lee et al., 2021 <sup>51</sup> ; Orlova et al., |
| $f_{CO_2}$                       | decreasing rate of soil CO <sub>2</sub> emissions (%)                        | 2019 <sup>52</sup> ; Song et al., 2016 <sup>53</sup>                            |
| $E_{CH_4}$                       | original soil CH <sub>4</sub> emissions ( $t \cdot ha^{-1} \cdot yr^{-1}$ )  | 0.2155 Tang et al., 2022 <sup>54</sup>                                          |
| $E_{N_2O}$                       | original soil N <sub>2</sub> O emissions ( $t \cdot ha^{-1} \cdot yr^{-1}$ ) | 0.0025 Woolf et al., 2016 <sup>55</sup>                                         |

| $E_{CO_2}$ | original soil CO <sub>2</sub> emissions ( $t \cdot ha^{-1} \cdot yr^{-1}$ ) |        |        |                                   | 0.3473                            | Wang et al., 2022 <sup>56</sup> |            |                  |
|------------|-----------------------------------------------------------------------------|--------|--------|-----------------------------------|-----------------------------------|---------------------------------|------------|------------------|
| $\gamma$   | optimal application rate ( $t \cdot ha^{-1}$ )                              |        |        |                                   | 20t/ha or 2 t/ha <sup>13,57</sup> |                                 |            |                  |
| Data       | Rice                                                                        | Wheat  | Maize  | Other<br>agricultural<br>residues | Grass<br>residues                 | Forestry<br>residues            | miscanthus | Sweet<br>sorghum |
| $f_{CH_4}$ | 0.0%                                                                        | 0.0%   | 0.0%   | 0.0%                              | 7.5%                              | -20.5%                          | 8.0%       | 0.0%             |
| $f_{N_2O}$ | -20.0%                                                                      | -18.0% | -18.0% | -18.0%                            | -2.5%                             | -40.4%                          | -33.0%     | -18.0%           |
| $f_{CO_2}$ | 12.0%                                                                       | 24.2%  | 20.7%  | 12.0%                             | 17.1%                             | 16.5%                           | 17.1%      | 12.0%            |

**Discussion on avoided soil greenhouse gas (GHG) emissions.** Previous studies highlighted the important role of biochar in soil GHG avoidance. Biochar application is anticipated to potentially decrease N<sub>2</sub>O emissions by around 20%, as indicated by previous experiments<sup>53,58</sup>, assuming a general range of 10–30 t/hm<sup>2</sup> for the applied biochar amount. On the other hand, experiments have also shown that the continuous application of biochar at the rate of 2 t/hm<sup>2</sup>/a could also lead to substantial avoidance of soil GHG emissions.

When the optimal application rate of biochar was assumed to be 20 t/hm<sup>2</sup>, the avoided soil N<sub>2</sub>O emissions were 3.84 Mt CO<sub>2</sub>eq/a under the sustainable technical scenario, i.e., only 0.4% of the carbon captured by biochar. This is because the amount of biochar application is usually insufficient to achieve the optimal application rate in practice. Similarly, the avoidance of soil CH<sub>4</sub> emissions was limited. In croplands, the avoidance of CH<sub>4</sub> emissions was not considered because research on CH<sub>4</sub> is controversial and the results from meta-analysis were insignificant<sup>50,53,59</sup>. In other land, the effects can even be the opposite<sup>50</sup>, which means that biochar application can increase soil CH<sub>4</sub> emissions. In terms of soil CO<sub>2</sub>, based on meta-analysis<sup>52,60</sup>, the priming effects in soil are also positive, which means that biochar can accelerate soil mineralization and increase soil CO<sub>2</sub> emissions. However, some studies have found that negative priming effects can be detected after a long period<sup>61</sup>. If the optimal application rate of biochar was assumed to be 2 t/hm<sup>2</sup>, the avoided or increased GHG emissions would be 10 times greater than those under the assumption of an application rate of 20 t/hm<sup>2</sup>. Further exploration on avoided soil greenhouse gas (GHG) emissions after applying biochar is needed in the future.

**Supplementary Figure 11 Avoided GHG emissions with the assumption of an optimal biochar application rate of 20 t/hm<sup>2</sup>.**



## 4.2 Yield increasing

The benefits of yield increasing from pyrolyzing one unit of biomass ( $B\_yield_i$ ) were calculated according to formula (4-2). The effects for one hectare of land at the optimal rate of biochar application were calculated by multiplying the yield ( $Yield_i$ , t/ha), price of crops ( $P_i$ , \$/t), and increasing rate of yield ( $\theta_i$ , %). Then, the effects were apportioned per unit of biomass by dividing by the optimal biochar application rate  $\gamma$  and multiplying by the weight conversion rate  $\alpha_i$ . Here, the value of  $\gamma$  was adopted as 20 t/ha for conservative estimation. The treatment applied here means to discount the effects of actual biochar application based on the optimal biochar application according to a linear relationship. This is a simplification and it can also be interpreted as a concentrated application on a small plot within a hectare of land after the biochar has been transported back to the harvesting site of the feedstock.

$$B\_yield_i = (\theta_i \cdot Yield_i \cdot P_i) \cdot \frac{1}{\gamma} \cdot \alpha_i \quad (4-2)$$

**Supplementary Table 11 Data and data sources related to yield increase**

| Parameters diverse in feedstocks |                                            |       |       |                          | Sources                                                                               |        |               |       |
|----------------------------------|--------------------------------------------|-------|-------|--------------------------|---------------------------------------------------------------------------------------|--------|---------------|-------|
| $Yield_i$ <sup>1</sup>           | yield (t/ha)                               |       |       |                          | China Statistical Yearbook 2019; Harvard Dataverse <sup>62</sup>                      |        |               |       |
| $\theta_i$                       | increasing rate of yield (%)               |       |       |                          | Meta-analysis:                                                                        |        |               |       |
|                                  |                                            |       |       |                          | -Agricultural crops: Xia et al., 2023 <sup>63</sup> ; Yu et al., 2023 <sup>64</sup> ; |        |               |       |
|                                  |                                            |       |       |                          | -Other: Singh et al., 2022 <sup>57</sup>                                              |        |               |       |
| $P_i$                            | price of crops or economic forestry (\$/t) |       |       |                          | State Administration of Grain, China                                                  |        |               |       |
| Data                             | Rice                                       | Wheat | Maize | Other agricultural crops | Grass                                                                                 | Forest | Sweet sorghum |       |
| $Yield_i$                        | 7.03                                       | 5.42  | 6.10  | diverse                  | 1.20                                                                                  | 5.00   | 20.60         | 12.87 |
| $\theta_i$ <sup>2</sup>          | 11.4%                                      | 14.4% | 10.5% | diverse                  | 53.0%                                                                                 | 18.0%  | 45.1%         | 35.0% |
| $P_i$ <sup>3</sup>               | 391                                        | 339   | 265   | 332                      | 121                                                                                   | 1662   | 175           | 175   |

Note: 1. Data of average yield was adopted from China Statistical Yearbook 2019. Data of yield at grid level was adopted from Harvard Dataverse<sup>62</sup> and our results about biomass spatial distribution; 2. The increasing rates of yield after biochar application on rice, wheat and maize are 9%, 14% and 13% according to Yu et al., 2023<sup>64</sup>, and those are 14%, 15%, and 8% according to Xia et al., 2023<sup>63</sup>. For simplification, we adopted average value of these two latest studies. In terms of grass residues, forestry residues, and dedicated energy crops. We adopted the value from meta-analysis at the world level; 3. The price of energy crops is determined by multiplying 17.5GJ/t by 10\$/GJ.

Given that biochar applied to soil with coarse or fine texture has been found to be more effective in improving crop yields, and soil pH also has an influence on the effectiveness of biochar application, we assumed that the effects of yield increase on coarse- and fine-texture soil or acidic soil would be 50% greater than the average value, while that on medium-texture soil or alkaline soil would be only half the average value<sup>57,65</sup>, as shown in formula (4-3):

$$B\_yield_i' = \begin{cases} B\_yield_i \cdot (1-50\%), & \text{if biochar is applied to medium-texture soil or alkaline soil} \\ B\_yield_i \cdot (1+50\%), & \text{if biochar is applied to coarse- or fine-texture soil or acidic soil} \end{cases} \quad (4-3)$$

## Supplementary Note 5 Economics of negative emission provided by biochar

We made the cost-benefit analysis (CBA) to identify the economics of negative emission provided by biochar. To be specific, the unit net cost of negative emissions ( $UC$ , \$/tCO<sub>2</sub>) was calculated using the net present value ( $NPV$ ) and the total negative emissions ( $TNE$ ) during the project lifetime ( $T$ ). The biomass pyrolysis plant was assumed capable of processing 80,000 t of biomass per year over 20 years.

$NPV$  of each plant can be formulated as:

$$NPV = -Inv + \sum_{t=1}^T \frac{(Income_t - Cost_t) \cdot (1+if)^t}{(1+r)^t} \quad (5-1)$$

$$UC = \frac{-NPV}{TNE} = \frac{-NPV}{\text{Annually biomass pyrolysed} \cdot \text{lifetime} \cdot Seq} \quad (5-2)$$

where  $Income_t$  and  $Cost_t$  are the income and cost in year  $t$ , respectively. For simplification, the discount rate  $r$  and inflation rate  $if$  is assumed to be the same in this study, implying these parameters doesn't change over time. Annual depreciation of the investment ( $Inv_t$ ) is calculated based on  $r$  and  $T$ , as shown in formula (5-3)

$$Inv_t = \frac{Inv}{(1-1/(1+r)^T)/r} \quad (5-3)$$

Then, the net cost  $UC_i$  was calculated by dividing the costs and incomes of pyrolyzing one unit of biomass  $i$  by  $Seq_i$ :

$$UC_i = \frac{1}{Seq_i} \cdot (C\_pur + C\_bmstor + C\_inv + C\_o\&m + u \cdot k + u \cdot k \cdot \alpha_i + v \cdot \alpha_i \cdot P\_gas \cdot Pro\_gas_i - B\_yield_i) \quad (5-4)$$

Where  $C\_inv$  is the initial investment,  $C\_pur$  is the purchasing cost,  $C\_bmstor$  is the biomass

storage cost,  $C_{o\&m}$  is the operating and maintaining costs,  $u$  and  $k$  represent the cost of transporting biomass and biochar, where  $u$  represents the transport cost per ton of biomass or biochar, and  $k$  represents the distance between the purchasing source and pyrolysis plant,  $v$  is the cost of biochar application, and  $\alpha_i$  is the conversion rate. The total income consists of syngas incomes, which were calculated using the price multiplied by the production amount, and the incomes from increased yields,  $B\_yield_i$ . Relevant data are listed in Supplementary Table 12.

**Supplementary Table 12 Data and data sources**

| Common parameters       |                                                                     | Data                                                 | Sources                                                                                                                   |                                                        |
|-------------------------|---------------------------------------------------------------------|------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|
| $C_{pur}$               | purchasing cost (\$/t biomass)                                      | 90 for energy crops and grass, 36 for other residues | Survey on pilot projects                                                                                                  |                                                        |
| $C_{bmstor}$            | biomass storage cost (\$/t biomass)                                 | 10                                                   |                                                                                                                           |                                                        |
| $C_{inv}$               | investment cost (\$/t biomass)                                      | 4.8                                                  |                                                                                                                           |                                                        |
| $C_{o\&m}$              | operating and maintaining cost (\$/t biomass)                       | 22.5                                                 |                                                                                                                           |                                                        |
| $P_{gas}$               | price of syngas (\$/GJ)                                             | 10.6                                                 |                                                                                                                           |                                                        |
| $u$                     | transport cost per ton biomass or biochar (\$/t/km)                 | 0.22                                                 | Research Report on Biomass Electricity Price Policy, 2018 <sup>66</sup>                                                   |                                                        |
| $k^a$                   | distance between the sources and pyrolysis plants (km)              | 21                                                   | Harvard Dataverse <sup>62</sup>                                                                                           |                                                        |
| $v$                     | application cost of biochar (\$/t biochar)                          | 13.4                                                 | 27.44\$/ha, Woolf et al.,2016 <sup>55</sup><br>0.07\$/kWh*53.11 kWh:<br>337.83 kg biochar, Yang et al.,2021 <sup>67</sup> |                                                        |
| Study                   | Technology type                                                     | $C_{inv}$                                            | $C_{o\&m}$                                                                                                                | $C_{pur}$                                              |
| Plant in Shenyang       | Fixed-bed biomass carbonization equipment                           | -                                                    | -                                                                                                                         | 36 -purchasing                                         |
| Plant in Inner Mongolia | Fixed-bed straw gasification and co-production of biochar           | 4.1                                                  | 17.9                                                                                                                      | 42 -purchasing<br>6 - transport                        |
| Plant in Heilongjia ng  | Continuous anaerobic carbonization                                  | 5.7                                                  | 13.5                                                                                                                      | 4 - storage<br>33 -purchasing<br>5 - transport         |
| Plant in Henan          | Gasification and co-production of biochar                           | 6.9                                                  | -                                                                                                                         | 5 - storage<br>53- purchasing<br>15 - processing<br>76 |
| Plant in Anhui          | Gasification and gas supply for 30t boiler co-production of biochar | 4.8                                                  | 27.2                                                                                                                      | - purchasing, transport, storage, breaking             |
| Plant in Guizhou        | Self-heating low-temperature pyrolysis                              | 6.1                                                  | 42.0                                                                                                                      | 33 - purchasing<br>8 - Transport                       |

Note: a. The heating value of medium-temperature and medium-pressure steam commonly used in industries at 400 degrees Celsius and 4 MPa is approximately 3.278 GJ/t, with a price of 250 RMB per ton. The energy

efficiency of the combustion furnace is 92%. Based on the heat value, we have calculated the price of synthetic gas.

b. Assuming that the plant is built at the center point of the grid, biomass will not be transported across the grids to control transportation costs.

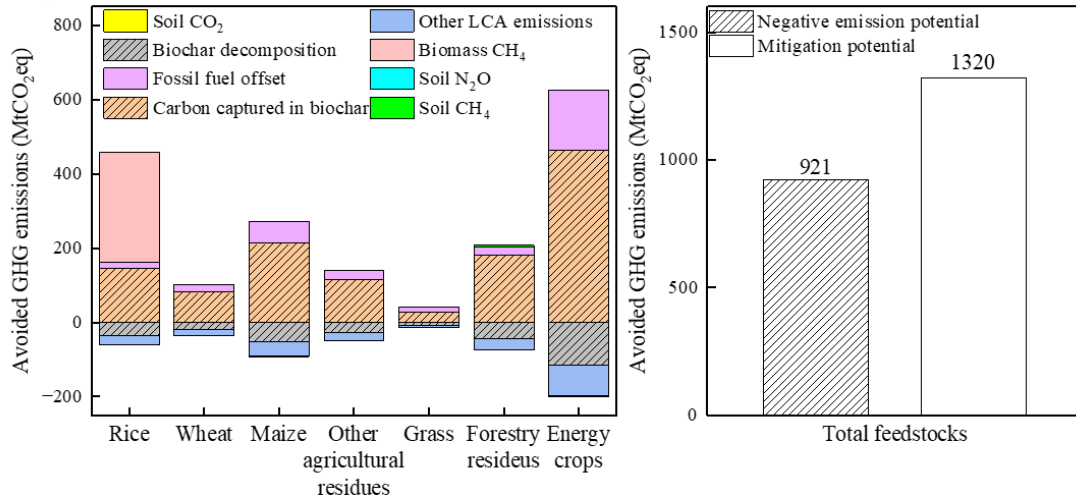
## **Supplementary Note 6 Mitigation potential of biochar**

Here, the mitigation potential of biochar included the carbon permanently preserved in biochar, the avoided soil GHG emissions, fossil fuel emission offsets, other life cycle emissions, and the avoided GHG emissions if residues are left in the field rather than used for biochar. The avoided soil GHG emissions were calculated as described in Note 4. Fossil fuel emission offsets refer to the emissions of fossil fuels avoided by using syngas. The emission factor for natural gas is 0.0543 tCO<sub>2</sub>/GJ<sup>41</sup>. Emissions from electricity consumption during operation and maintenance was deducted (90KWh/t biomass). The grid emission factor is 0.581 tCO<sub>2</sub>/MWh<sup>68</sup>. Additionally, we also accounted for other life-cycle emissions (125.4 kgCO<sub>2</sub>eq/t biomass) during the feedstock processing and transportation, plant construction, water treatment, and biochar application<sup>49,67,69,70</sup>. In the context of biomass GHG emissions, only avoided CH<sub>4</sub> emissions were considered: rice residues left on paddy land have the potential to increase CH<sub>4</sub> emissions by 110.7%<sup>71</sup>. Finally, the mitigation potential that varies depending on the optimal biochar application rate was determined as 1,320–1,354 MtCO<sub>2</sub>eq, i.e., 43% and 47% greater than the negative emission potential, respectively.

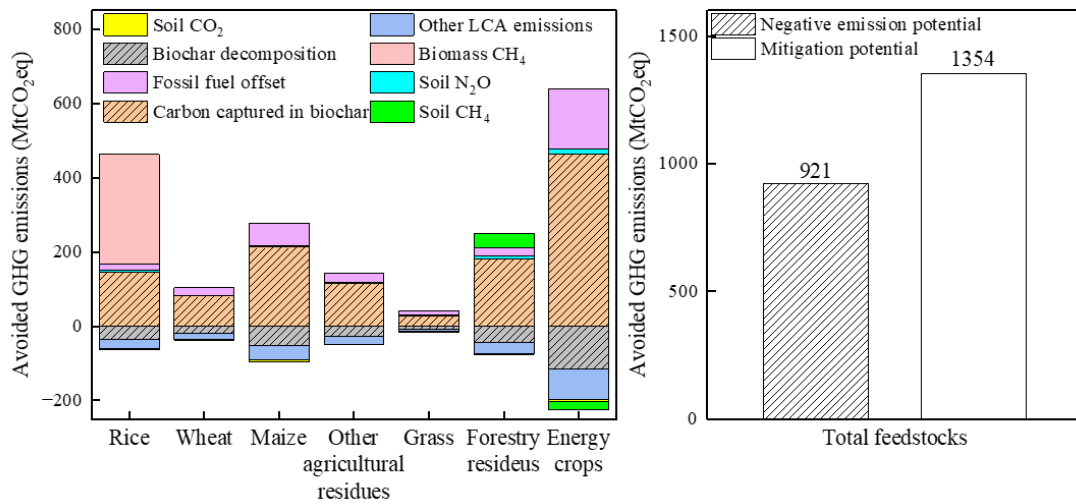
It is worth noting that the baseline used to assess the mitigation potential in this study corresponds to the current situation. Fossil fuel emission offsets, for example, was calculated as the differences between syngas and natural gas required to produce the same quantity of industrial stream. Another alternative option for energy production, namely BECCS, which is likely to be used in the future, is not considered in this study. The by-product of BECCS can be electricity, which implies a higher energy availability and is more ready-to-use than by-products of pyrolysis. On the other hand, limitations associated with BECCS are obvious, mainly including high carbon capture costs, poorly constructed carbon transport pipelines (especially in China where there is a serious mismatch of biomass sources and basin sinks), and the potential for carbon leakage and geological risks. Besides, the availability of residues for BECCS might be lower compared to biochar due to the necessity of maintaining soil fertility, and the left residues in field might also result in soil GHG emissions. In general, the comparison of biomass-based negative emission technologies needs further investigation.

**Supplementary Figure 12 Mitigation potential of biochar under the sustainable technical scenario.** The shaded bars represent the negative emission potential calculated in this study. All avoided GHG emissions represent mitigation potential. Note that avoided soil CO<sub>2</sub> can also be considered as negative emissions, but here we only count it as part of the mitigation potential.

### Optimal biochar application rate -20t/hm<sup>2</sup>



### Optimal biochar application rate -2t/hm<sup>2</sup>



## Supplementary Note 7 Uncertainty analysis

Using Monte Carlo simulation, we performed uncertainty analyses of the negative emission potentials and costs. The parameter ranges are shown in Supplementary Table 13. Random values were generated according to the normal distribution and triangular distribution. On the basis of existing literature, we adopted the mean  $\mu$  and 95% confidence interval for each parameter, from which the standard deviation  $\sigma$  was calculated. After 10,000 iterations, we determined the uncertainty as a range. Consequently, the negative emission potential of biochar was estimated at 1.07 GtCO<sub>2</sub>/a [0.68–1.46 GtCO<sub>2</sub>/a, 95% confidence interval], and the negative emission cost of biochar was estimated at 92 \$/tCO<sub>2</sub> [-13–197 \$/tCO<sub>2</sub>, 95% confidence interval].

**Supplementary Table 13 Key parameters for uncertainty analyses**

| Triangular distribution     | Lower limit | Mode   | Upper limit |
|-----------------------------|-------------|--------|-------------|
| $C_{pur}$                   | 30          | 36     | 90          |
| $C_{inv}$                   | 4.1         | 4.8    | 6.9         |
| $C_{o\&m}$                  | 17.9        | 22.5   | 27.2        |
| Biomass - rice <sup>a</sup> | -9%         | -0.77% | 5.6%        |

| Biomass - wheat        | -21%        | -4.11%         | 13%                             |
|------------------------|-------------|----------------|---------------------------------|
| Biomass - maize        | -29%        | 0.28%          | 41%                             |
| Biomass - forestry     | 11%         | 91%            | 192%                            |
| Biomass - energy crops | -4.3%       | -0.63%         | 41.5%                           |
| $\theta_i$             | 11%         | 18%            | 53%                             |
| Normal distribution    | range       | Mean ( $\mu$ ) | Standard deviation ( $\sigma$ ) |
| $u$                    | 0.15~0.25   | 0.20           | 0.0301                          |
| $k$                    | 0~50        | 25             | 15.1989                         |
| $v$                    | 10.7~16.1   | 13.4           | 1.6293                          |
| $d$                    | 10%~40%     | 25%            | 0.0912                          |
| $Yield_i$              | 1.2~11.0    | 6.1            | 2.9668                          |
| $P_i$                  | 265.3~398.0 | 331.6          | 40.3197                         |
| $\alpha_i$             | 23.2%~34.8% | 29%            | 0.0353                          |
| $\beta_i$              | 53%~79%     | 66%            | 0.0803                          |
| $P_{gas}$              | 8.5~12.7    | 10.6           | 1.2889                          |
| Energy efficiency      | 0.53~0.89   | 0.71           | 0.1079                          |

Note a: detailed information is shown below.

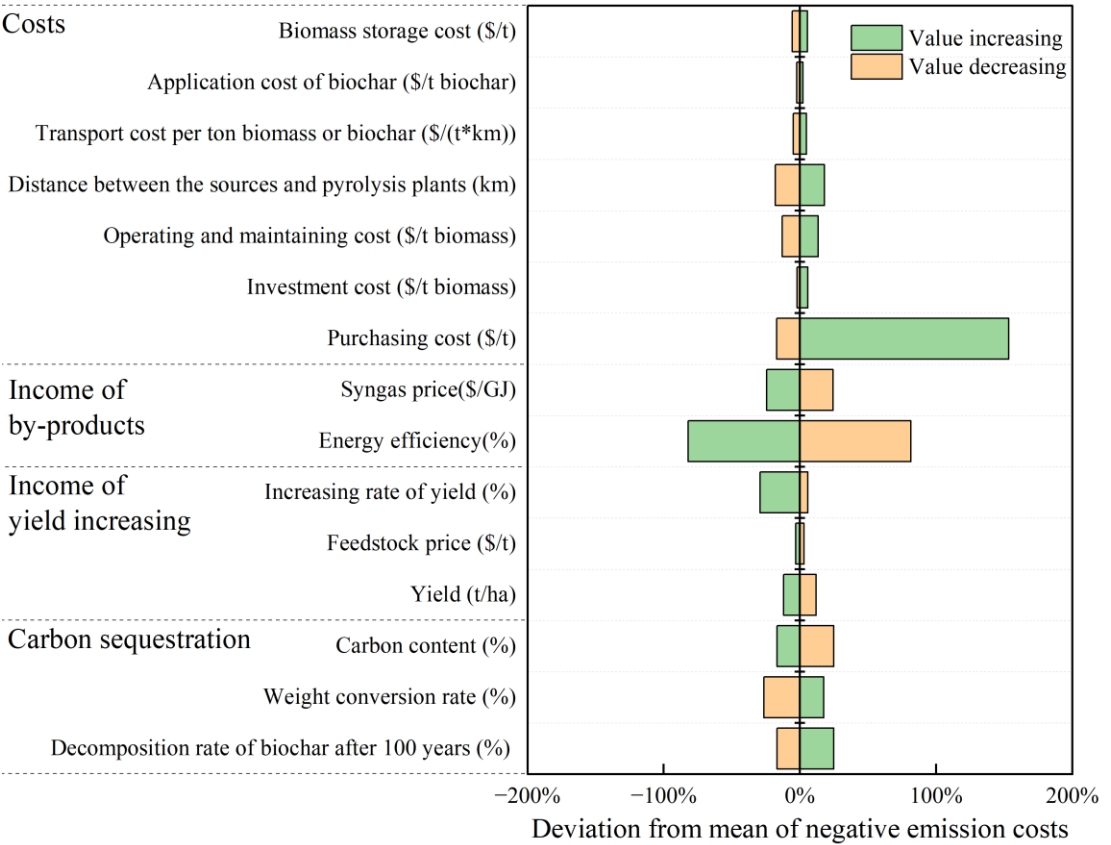
When determining the range of available biomass resources, we assumed a close correlation between agricultural and forestry residues and their productions. To estimate future crop production, a common approach is to quantify the climate impact on crop yield and incorporate it into crop models or economic models to obtain crop production projections under various scenarios. According to existing studies on major grain crops, there is significant uncertainty in yield changes for major grain crops in the second half of the 21st century. For example, the change of rice yield could range from -9% to 5.6%, wheat from -21% to 13%, and maize from -29% to 41%<sup>72-77</sup>. Similarly, forestry residues are highly related to the forestry production. Studies have shown that under current climate conditions, carbon stocks are expected to significantly increase by 2060, and may even increase further under climate change scenarios like RCP4.5 and RCP8.5. Assuming linear growth, the increasing rate of biomass stock could range from 11% to 192% by 2060, with the median being 91%<sup>78-80</sup>.

When conducting uncertainty analysis, we solely considered the influence of climate on biomass resources. However, it should be noted that socio-economic scenarios also have an impact on biomass production. According to AR6 Scenario Explorer and Database<sup>81</sup>, IAMs that consider both socio-economic scenarios and climate scenarios show that the change of crop production compared to 2020 could range from -21% to 75.5% in 2060 (AIM/CGE, C3IAM, IMAGE), and the change of forestry production could range from -23% to -6 % in 2060 (AIM/CGE, IMAGE) in terms of ‘Counties of centrally-planned Asia; primarily China’. In general, the estimates of production are influenced by complex mechanisms, such as technological competition, carbon pricing, land-use policies, etc., which need to be explored in a broader framework.

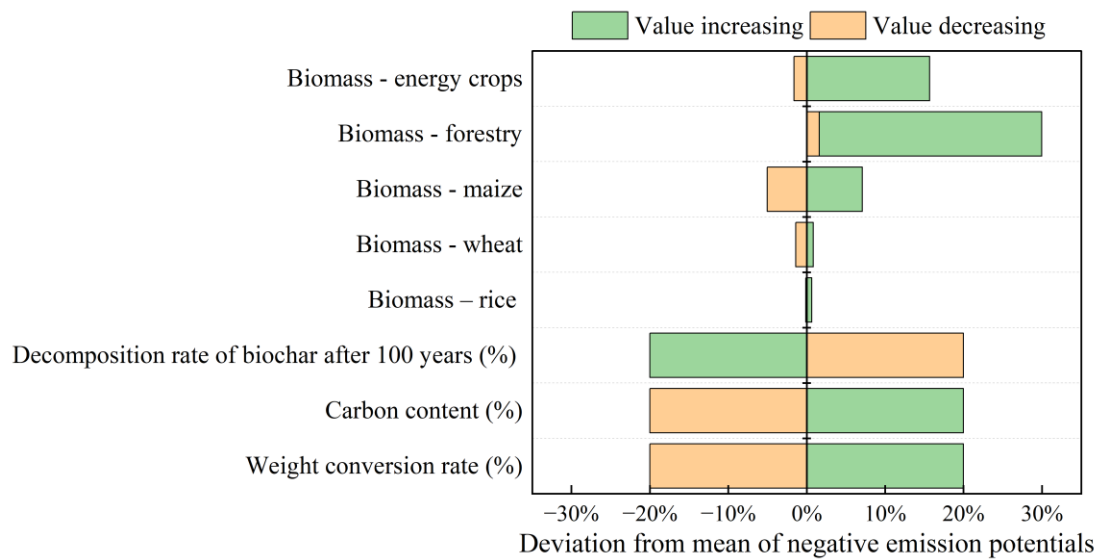
As for energy crops, their productions are closely related to acreage and yields. Our assumptions about marginal land for energy plantations are conservative, and energy crop does not compete with food for land. To be specific, in the current technical scenario, the sustainable technical scenario and the maximum theoretical scenario of our study, we assumed no energy plantations, limited cultivation that adheres to ecological constraints, and all marginal land cultivation,

respectively. In terms of the impacts of future climate change on energy crop yields, we refer to Nie et al.<sup>20</sup> for an estimate of yield change intervals in 2060.

**Supplementary Figure 13 Sensitivity analysis of parameters affecting the net costs of negative emissions**



**Supplementary Figure 14 Sensitivity analysis of parameters affecting the negative emission potentials.**



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