Supporting Information for: **Research on China’s Sludge Production Pattern, Prediction and Carbon Emission Reduction Potential**

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## 1 Sludge Data Calculation

Sludge data in China are collected by the Ministry of Housing and Urban-Rural Development of the People’s Republic of China (MOHURD). MOHURD publishes *Urban Construction Yearbook* (MOHURD, 2019) every year, with yearly sludge production in each city. However, some data from this *Yearbook* has deficits. To eliminate the bias and inconsistency, we collected the information from *Urban Drainage Yearbook (CUWSDA, 2019)* which contains the yearly treatment data of all the wastewater treatment plants (WWTPs) in China. We used the name of WWTP to find its location (coordinate) through Baidu map. Identifying the city where the WWTP locates and summing all the sludge data of each WWTP in that city. Finally, we used our calculation to substitute the biased data in the *Urban Construction Yearbook* (Fig. S1.).

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| 图形用户界面, 应用程序  描述已自动生成  **Fig. S1.** The workflow for obtaining China’s sludge data at city level. |

Sludge production highly correlates to wastewater treatment flow (Fig. S2.). Based on this correlation, we calculated the sludge production of each wastewater treatment plants in China with the following equation:

Where *Ds* represents dry sludge, *F* is the flow of wastewater treatments and *s* is the conversion coefficients which were obtained from *Urban Drainage Statistical Yearbook* (Table S1)*.*

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| 图表, 散点图  描述已自动生成  **Fig. S2.** Correlation between sludge generation and the quantity of wastewater treated |

We grouped sludge production data by prefecture level, calculating the sum of sludge production in a city. Compared our calculation with *Urban Construction Yearbook,* fixed its inconsistency.

|  |  |
| --- | --- |
| ***Province*** | ***S (t/10 Kts)*** |
| Beijing | 7.31 |
| Tianjin | 5.95 |
| Hebei | 8.26 |
| Shanxi | 7.51 |
| Inner Mongolia | 6.98 |
| Liaoning | 4.61 |
| Jilin | 4.13 |
| Heilongjiang | 5.60 |
| Shanghai | 4.56 |
| Jiangsu | 6.43 |
| Zhejiang | 9.95 |
| Anhui | 4.61 |
| Fujian | 4.01 |
| Jinagxi | 3.07 |
| Shandong | 7.85 |
| Henan | 6.55 |
| Hubei | 4.65 |
| Hunan | 3.29 |
| Guangdong | 4.00 |
| Guangxi | 3.37 |
| Hainan | 3.48 |
| Chongqing | 6.04 |
| Sichuan | 5.31 |
| Guizhou | 3.56 |
| Yunnan | 4.77 |
| Tibet | 2.27 |
| Shaanxi | 7.83 |
| Gansu | 9.92 |
| Qinghai | 6.22 |
| Ningxia | 7.55 |
| Xinjiang | 7.91 |

**Table S1** Conversion coefficient for calculating sludge generation by wastewater treatments.

# 2 Scenario Analysis

In our SSP scenario analysis, we made an estimation for four of our sludge driving factors UR, LDP, BA and FCE. An logistic growth pattern were implemented for predicting the future trends of those variables.

The Logistic growth expression is:

（3）

Where *K* is the limit of growth, *P0*is the initial value (2002 was the first year in this paper), *t* is the year and *r* is the growth rate. We set different r to simulate SSP1 to SSP5 scenarios (See next part) (Table S2).

## *2.1 GDP and Population growth under SSPs*

Some scholars have used population and economic census data combined with the Cobb-Douglas economic predicting model to forecast the total GDP under different SSP scenarios in China(Fig. S3). The results show that under the SSP1 and SSP4 paths, GDP tends to increase and then decrease, reaching a peak around 2075, while under the SSP2 and SSP5 paths, GDP tends to increase. Under the regional competition path (SSP3), GDP growth is stagnant after 2050 (Jiang et al., 2018).

In terms of population (Fig. S4), the SSP3 path has the largest population growth, peaking at 1.427 billion in 2035, while the rest of the SSP paths show an increasing and then decreasing trend; the SSP4 path, which focuses on adaption challenges has the smallest population of 702 million. (Jiang et al., 2017).

The dataset of GDP growth of each province under different SSP scenarios was provided by Professor Jiang Tong’s team at Nanjing University of Information Engineering. We spatially connected the grid point data with the vector of China’s administrative divisions in ArcMap to obtain the projection data up to 2060 at provincial level.

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| 电脑屏幕的照片  低可信度描述已自动生成  **Fig. S3.** GDP growth forecasting based on Cobb-Douglas model at sub-province level. |

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| 图片包含 游戏机  描述已自动生成  **Fig. S4.** Population growth forecasting under SSP1 -SSP5 scenarios at sub-province level. |

## *2.2 Changes in urban infrastructure in China under SSPs*

The growth of built-up area (BA) and length of drainage pipelines (LDP), which are important factors influencing sludge production, contribute significantly to the increase of sludge. In this section, BA and LDP are predicted to give the change of urban infrastructure level under different scenarios.

There is a close relationship between BA and UR, and as urbanization progresses (Fig. S7), the urban built- up area will continue to grow. Some scholars have combined time series data and economic panel data, such as GDP and population, to predict the built-up area, and have achieved more accurate results (Tian et al., 2020). In general, urban infrastructure tends to grow year by year, and its growth rate will continue to decrease and eventually reach a limit level. (Zheng Xinqi et al., 2013) predicted the limit of urban construction land under different population policies in China by using a logistic growth model, and the results showed that the limit of built-up area in China is between 80,000 and 140,000 km2 . Based on this, this paper predicts the built-up area(Fig. S5) and drainage pipe length(Fig. S6) in China under different SSP scenarios by logistic growth .

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| 图片包含 游戏机  描述已自动生成  **Fig. S5.** BA growth forecasting under SSP1 -SSP5 scenarios at sub-province level.(Logistic Growth) |

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| 图片包含 游戏机  描述已自动生成  **Fig. S6.** LDP growth forecasting under SSP1 -SSP5 scenarios at sub-province level.(Logistic Growth) |

The upper limits of the built-up area and drainage pipe length vary across the country under different SSP scenarios, and the built-up area 21 converges to 80,000 km2 under the SSP1 path. The SSP2 scenario is similar to the existing growth rate, with the built-up area and drainage pipe length converging to 130,000 km2 and 1.58 million km , respectively. SSP5, with large-scale urban construction and economic construction, converges to 140,000 km2 and 1.6 million km respectively. To sum up, the development trend of urban infrastructure in each province from 2020 to 2060is obtained by fitting the development trend of built-up area and length of drainage pipes in each province from 2002 to 2019 using the least squares method with different growth limits and using the data of built-up area and length of drainage pipes in each province in 2002 as the starting year.

**Table S2** Growth rate (r) in different SSPs scenario at sub-provincial level

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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|  | **SSP1 (Low)** | | | | **SSP2 (Medium)** | | | | **SSP3 (High)** | | | | **SSP4 (Medium)** | | | | **SSP5 (High)** | | | |
| **Province** | **UR** | **LDP** | **BA** | **FCE** | **UR** | **LDP** | **BA** | **FCE** | **UR** | **LDP** | **BA** | **FCE** | **UR** | **LDP** | **BA** | **FCE** | **UR** | **LDP** | **BA** | **FCE** |
| Beijing | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Tianjin | 0.10 | 0.15 | 0.12 | 0.16 | 0.08 | 0.13 | 0.09 | 0.13 | 0.07 | 0.13 | 0.09 | 0.12 | 0.09 | 0.14 | 0.10 | 0.15 | 0.06 | 0.12 | 0.12 | 0.11 |
| Hebei | 0.13 | 0.15 | 0.12 | 0.14 | 0.11 | 0.13 | 0.09 | 0.11 | 0.10 | 0.13 | 0.09 | 0.10 | 0.12 | 0.14 | 0.10 | 0.13 | 0.09 | 0.12 | 0.12 | 0.09 |
| Shanxi | 0.13 | 0.15 | 0.12 | 0.13 | 0.11 | 0.13 | 0.09 | 0.10 | 0.10 | 0.13 | 0.09 | 0.09 | 0.12 | 0.14 | 0.10 | 0.12 | 0.09 | 0.12 | 0.12 | 0.08 |
| Inner Mongolia | 0.13 | 0.15 | 0.12 | 0.18 | 0.11 | 0.13 | 0.09 | 0.15 | 0.10 | 0.13 | 0.09 | 0.14 | 0.12 | 0.14 | 0.10 | 0.17 | 0.09 | 0.12 | 0.12 | 0.13 |
| Liaoning | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Jilin | 0.07 | 0.15 | 0.12 | 0.15 | 0.05 | 0.13 | 0.09 | 0.12 | 0.04 | 0.13 | 0.09 | 0.11 | 0.06 | 0.14 | 0.10 | 0.14 | 0.03 | 0.12 | 0.12 | 0.10 |
| Heilongjiang | 0.07 | 0.15 | 0.12 | 0.15 | 0.06 | 0.13 | 0.09 | 0.12 | 0.05 | 0.13 | 0.09 | 0.11 | 0.06 | 0.14 | 0.10 | 0.14 | 0.04 | 0.12 | 0.12 | 0.10 |
| Shanghai | 0.12 | 0.15 | 0.12 | 0.13 | 0.10 | 0.13 | 0.09 | 0.10 | 0.09 | 0.13 | 0.09 | 0.09 | 0.11 | 0.14 | 0.10 | 0.12 | 0.08 | 0.12 | 0.12 | 0.08 |
| Jiangsu | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Zhejiang | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Anhui | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Fujian | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Jinagxi | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Shandong | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Henan | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Hubei | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Hunan | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Guangdong | 0.07 | 0.15 | 0.12 | 0.15 | 0.06 | 0.13 | 0.09 | 0.12 | 0.05 | 0.13 | 0.09 | 0.11 | 0.06 | 0.14 | 0.10 | 0.14 | 0.04 | 0.12 | 0.12 | 0.10 |
| Guangxi | 0.02 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Hainan | 0.12 | 0.15 | 0.12 | 0.18 | 0.10 | 0.13 | 0.09 | 0.15 | 0.09 | 0.13 | 0.09 | 0.14 | 0.11 | 0.14 | 0.10 | 0.17 | 0.08 | 0.12 | 0.12 | 0.13 |
| Chongqing | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Sichuan | 0.12 | 0.15 | 0.12 | 0.18 | 0.10 | 0.13 | 0.09 | 0.15 | 0.09 | 0.13 | 0.09 | 0.14 | 0.11 | 0.14 | 0.10 | 0.17 | 0.08 | 0.12 | 0.12 | 0.13 |
| Guizhou | 0.18 | 0.15 | 0.12 | 0.15 | 0.15 | 0.13 | 0.09 | 0.12 | 0.14 | 0.13 | 0.09 | 0.11 | 0.17 | 0.14 | 0.10 | 0.14 | 0.13 | 0.12 | 0.12 | 0.10 |
| Yunnan | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Tibet | 0.12 | 0.15 | 0.12 | 0.20 | 0.10 | 0.13 | 0.09 | 0.18 | 0.09 | 0.13 | 0.09 | 0.17 | 0.11 | 0.14 | 0.10 | 0.19 | 0.08 | 0.12 | 0.12 | 0.16 |
| Shaanxi | 0.13 | 0.15 | 0.12 | 0.15 | 0.11 | 0.13 | 0.09 | 0.12 | 0.10 | 0.13 | 0.09 | 0.11 | 0.12 | 0.14 | 0.10 | 0.14 | 0.09 | 0.12 | 0.12 | 0.10 |
| Gansu | 0.12 | 0.15 | 0.12 | 0.20 | 0.10 | 0.13 | 0.09 | 0.18 | 0.09 | 0.13 | 0.09 | 0.17 | 0.11 | 0.14 | 0.10 | 0.19 | 0.08 | 0.12 | 0.12 | 0.16 |
| Qinghai | 0.12 | 0.15 | 0.12 | 0.20 | 0.10 | 0.13 | 0.09 | 0.18 | 0.09 | 0.13 | 0.09 | 0.17 | 0.11 | 0.14 | 0.10 | 0.19 | 0.08 | 0.12 | 0.12 | 0.16 |
| Ningxia | 0.12 | 0.15 | 0.12 | 0.15 | 0.10 | 0.13 | 0.09 | 0.12 | 0.09 | 0.13 | 0.09 | 0.11 | 0.11 | 0.14 | 0.10 | 0.14 | 0.08 | 0.12 | 0.12 | 0.10 |
| Xinjiang | 0.12 | 0.15 | 0.12 | 0.20 | 0.10 | 0.13 | 0.09 | 0.18 | 0.09 | 0.13 | 0.09 | 0.17 | 0.11 | 0.14 | 0.10 | 0.19 | 0.08 | 0.12 | 0.12 | 0.16 |

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| 图片包含 游戏机  描述已自动生成  **Fig. S7.** UR growth forecasting under SSP1 - SSP5 scenarios at sub-province level.(Logistic Growth) |

## *2.3 Changes in Chinese residents’ lifestyles under SSPs*

The lifestyle of residents, especially their dietary habits, has a significant impact on the increase of sludge. The SSPs does not describe the changes in the dietary habits of the population. However, with the socio-economic progress and improvement of population quality, the dietary structure of China’s population will tend to be rationalized. According to the Scientific Research Report on China Dietary Guidelines 2021 (Table S3), Chinese residents should focus on plant-based diet, optimize the structure of animal food consumption, and control the intake of oil and salt. It is estimated that an adult will consume about 170-300g of carbon per day, part of which will be used to supply energy for human activities and part of which will eventually be discarded and become a major source of sludge. In this paper, we assess the changes in sludge production due to changes in the diet of the population. The trend in the daily intake of meat, non-nutritional calories and total calories is more consistent across regions as income increases, showing an increase followed by saturation(David et al., 2014).

**Table S3**. Reasonable Intake of Recommendation Diet from China Dietary Guidelines 2021

|  |  |  |
| --- | --- | --- |
| **Food Type** | **Reasonable Intake (g)** | **Carbon Contents (g)** |
| Cereal and potato staples | 250-400 | 80-130 |
| Whole grains | 50-150 | 15-50 |
| Vegetables and fruits | 500-850 | 25-45 |
| Livestock and poultry | 40-75 | 10-20 |
| Eggs | 40-50 | 10-15 |
| Aquatic products | 40-75 | 5-10 |
| Soybeans and nuts | 25-35 | 5-10 |
| Milk products | 300 | 20 |
| Total | 1245-1900 | 170-280 |

For SSP1, the whole society has a strong awareness of sustainable development, and as the population’s education level increases, residents’ environmental awareness increases and their dietary habits are based on environmental reduction goals. For SSP2, the environmental awareness of residents is moderate, economic development is highly uneven, and overall, carbon emissions caused by residents’ living habits are at a moderate level. For SSP3, regional competition is developing and residents’ habits are aggressive, resulting in high carbon emissions. For SSP4, the regional uneven development is significant, and its carbon emissions are slightly lower than those of SSP3. For SSP5, global economic development is concentrated without considering the environmental consequences and has the highest carbon emissions. We multiply population and different carbon contents intake under different SSPs to calculate the growth of CCF(Fig. S7). Also the FCE was calculated by multiply population with FCE per capita.(Fig. S8)

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| 图片包含 游戏机, 大  描述已自动生成  **Fig. S8.** CCF growth forecasting under SSP1 -SSP5 scenarios at sub-province level. |

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| 电脑屏幕的照片上有字  低可信度描述已自动生成  **Fig. S9.** FCE growth forecasting under SSP1 -SSP5 scenarios at sub-province level.(Logistic Growth) |

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