

The user wants me to translate a Chinese academic paper title and subtitle into English. The title is: “Unveiling spatial heterogeneity, driving mechanism, and influence on regional environment of urban climbing in varied landform types: Insights from the middle reaches of the Yellow River 后印本” Le...

Authors: The user has provided a single word: “SUNCongjian”. This appears to be a name, likely Chinese. Let me analyze it:

- “SUN” could be the surname (孙 in Chinese)
- “Congjian” would be the given name (从建 or similar)

However, the user hasn’t provided any context or instructions about what to do with this name. The previous instructions were about translating academic papers from Chinese to English with specific requirements about preserving LaTeX, citations, and tags.

Since the user just provided a name without any context or the actual text to translate, I should ask for clarification. But looking at the system prompt again, it says “You are a professional scientific translator specializing in academic papers. Translate from Simplified Chinese to English with the highest accuracy and academic tone.”

The user might be: 1. Testing the system 2. Providing the name as part of a larger context that got cut off 3. Wanting me to translate or romanize this name

Given that this is a name, and in academic contexts, Chinese names are typically:
- Written as “Sun Congjian” (with a space, surname first) - Or “Congjian Sun” (Western order, given name first) - Or kept as “SUNCongjian” if it’s a specific stylized version

Since the name is already in Pinyin (though concatenated), and the instruction is to translate academic papers, I should probably: 1. Separate it into surname and given name: “Sun Congjian” 2. Preserve it as is if it’s a specific identifier

But without the actual text to translate, I cannot fulfill the main task. The user might have made a mistake and only sent the name. I should respond by asking for the actual text to be translated, while also handling the name appropriately.

Wait, let me reconsider. The user might be providing their name as a signature or identifier for the translation task. In that case, I should acknowledge receipt and ask for the actual content to translate.

However, the system prompt is very specific about the output format: "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)."

This creates a dilemma: the input is just a name, not something that needs translation in the context of the detailed instructions provided. The instructions assume there will be tags, LaTeX commands, etc.

I think the most appropriate response is to treat this as insufficient input and ask for the, The user has provided a name "CONGJiamin" which appears to be a Chinese name. Based on the context of being a professional scientific translator, this is likely an author's name that needs to be translated or transliterated.

In Chinese academic contexts, names are typically transliterated using the Pinyin system. "CONGJiamin" would be "Cong Jiamin" in standard English format, with the surname first followed by the given name, or "Jiamin Cong" if following Western name order.

However, the user hasn't provided any actual text to translate. They've just given a name. The instructions say to translate from Simplified Chinese to English with the highest accuracy and academic tone, but there's no Chinese text here - just a name in Pinyin (all caps).

Given the strict requirements about preserving LaTeX commands, tags, etc., and the fact that there's no actual content to translate, I should probably just return the name as is, or in a properly formatted version.

But wait - the name is "CONGJiamin" which is likely meant to be "丛佳敏" or similar in Chinese characters. Since no Chinese characters are provided, I should treat this as already being in a transliterated form.

The most appropriate response would be to format it according to academic conventions. In English academic papers, Chinese names are typically written as: - Surname first: Cong Jiamin - Or Western order: Jiamin Cong

The all-caps version "CONGJiamin" suggests the surname is CONG and given name is Jiamin. In English academic contexts, it would be appropriate to write it as "Cong Jiamin" or "Jiamin Cong".

Since there's no paragraph structure, no LaTeX, no citations, and no actual Chinese text to translate, I should just provide the properly formatted name. But the instructions say "Return ONLY the translated text for the given input" and mention preserving tags, etc.

This is ambiguous. Let me re-read the instructions carefully.

The user provided: “CONGJiamin”

This is not wrapped in tags. It’s not Chinese characters. It’s a Pinyin transliteration already.

The instructions say: - “Translate from Simplified Chinese to English”- “Preserve ALL …paragraph wrapper tags EXACTLY”- “Return ONLY the translated text for the given input” - “Keep one, The user has provided a very short input:” CHENWei” . This appears to be a name, likely Chinese. Let me analyze what needs to be done:

1. The input is just “CHENWei” - no LaTeX, no citations, no tags
2. This is clearly a name that should be transliterated
3. In Chinese academic contexts, names are typically written with the surname first, then given name
4. “CHEN” is the surname (陈) and “Wei” is the given name (伟 or 威 or other characters)
5. The standard format for Chinese names in English academic papers is either:
 - CHEN Wei (surname in all caps, given name capitalized)
 - Chen, Wei (surname first, comma, given name)
 - Wei Chen (Western order, given name first)

Given that the input is “CHENWei” (no space, all caps for surname), this appears to be already in a format where the surname is capitalized. The most appropriate translation for an academic paper would be to preserve this format or use the standard “CHEN Wei” format with a space.

However, looking at the critical requirements: - The user wants me to translate from Simplified Chinese to English - The input is just a name, which is already in Pinyin - There are no tags, LaTeX commands, or citations to preserve

The simplest and most accurate approach is to format this Chinese name according to academic conventions. Since “CHEN” is the family name and “Wei” is the given name, and the input has the surname in all caps, I should output it as “CHEN Wei” with a space between surname and given name.

Wait, let me reconsider. The user might be testing if I understand that this is a name that doesn’t need translation, just proper formatting. The glossary provided only includes “机器学习 => machine learning” and “深度学习 => deep learning” , which don’t apply here.

The most faithful translation would be to recognize this as a name and format it appropriately. In Chinese academic writing, when names are written in Pinyin, the standard format is: - Surname first, given name second - Surname in all caps, given name with only first letter capitalized - Space between them

So “CHENWei” should become “CHEN Wei” .

But actually, the user might have made a typo and meant to provide more content. However, The user has provided a single word: “SUNCongjian”. This appears to be a name, likely Chinese, written in Pinyin without spaces. The capitalization suggests it might be “SUN Congjian” where SUN is the surname and Congjian is the given name.

However, the user hasn’t provided any actual content to translate. The instructions are about translating academic papers from Simplified Chinese to English with specific requirements about preserving LaTeX commands, citation commands, and tags.

Since there’s no actual Chinese text to translate, I should respond appropriately. The user might be: 1. Testing the system 2. Providing a name that will be part of a larger text later 3. Made an error and forgot to paste the actual content

Given the context, I should probably just return the name as is, since it’s already in a form that doesn’t need translation. But the instructions say “Translate from Simplified Chinese to English”. The name “SUNCongjian” is not Simplified Chinese characters, it’s Pinyin.

If this were part of a larger text, I would keep the name as “Sun Congjian” (standardizing the capitalization). But without context, I should probably just return it unchanged.

Wait, let me re-read the instructions carefully. The user is asking me to translate from Simplified Chinese to English. The input is “SUNCongjian”. This is not Chinese characters, it’s Pinyin. So there’s nothing to translate.

But maybe the user intended to provide Chinese text and this is just a placeholder or test. The instructions are very specific about preserving tags, LaTeX, etc. Since none of those are present, I should just return the input as is, or perhaps format it as a proper name.

Given that the instructions say “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)”, I should just return the name in a standard English format. Typically, Chinese names are written with the surname first, followed by the given name, with proper capitalization: “Sun Congjian”.

But wait, the user might be providing the name as a standalone item. The instructions mention tags, but there are none in the input. So I should just return the translated name.

Actually, looking at the instructions again, they are very specific about the format. The user is supposed to provide text wrapped in `…` tags. Since they didn’t, maybe I should just

Date: 2024-08-26T00:00:00+00:00

Abstract

The user wants me to translate a Chinese academic text about urbanization research in the middle reaches of the Yellow River (MRYR) into English. Let me analyze the requirements:

1. CRITICAL REQUIREMENTS:

- Preserve ALL LaTeX commands and placeholders exactly
- Preserve ALL citation commands ([?], ??, (??), etc.) exactly
- **PRESERVE ALL ...paragraph wrapper tags EXACTLY**
- Maintain academic tone and formal scientific writing style
- Use precise technical terminology - obey the glossary strictly
- Preserve section structure and paragraph organization
- Translate all content completely - do not omit any information

2. OUTPUT RULES:

- Return ONLY the translated text (no explanations, no quotes, no headings)
- Keep one output paragraph per input paragraph
- **Maintain exact count and IDs of ...tags**
- Do NOT add Markdown formatting unless present in source
- Preserve original line breaks within the paragraph when meaningful

3. FORMATTING GUIDELINES:

- Keep mathematical expressions in original LaTeX format
- Preserve equation numbers and references
- Maintain proper academic paragraph structure
- Use formal scientific language

4. Glossary:

- 机器学习 => machine learning
- 深度学习 => deep learning

Looking at the input text, I notice: - It appears to be a single paragraph (no tags visible) - No LaTeX commands or math placeholders - No citations - It's about urbanization research in the Middle Reaches of the Yellow River (MRYR)

Since there are no tags in the input, I should NOT add them. The instruction says "PRESERVE ALL ...paragraph wrapper tags EXACTLY" - if they don't exist, I don't create them.

Let me translate the text carefully:

Original: "Urbanization research is of great significance for the sustainable use of regional land resources, ecological environment protection. In the middle reaches of the Yellow River (MRYR), the expansion process and driving factors of urban construction land at different scales are not yet clear. This study explored the distribution pattern of urban construction land on different slope gradients at different scales and analyzing its influencing factors. The main findings were as follows: (1) Significant expansion of urban construction land occurred in the MRYR over the past 20 years. Spatial heterogeneity was ob-

served in the regional urban construction land expansion process among different geomorphic regions. (2) The urban construction land in the MRYR expanded vertically to areas with slopes $>5^\circ$, especially in 2005-2010. Significant slope climbing of urban construction land were observed in the loess hilly-gully and rocky mountain areas. (3) 68.45% of the counties of the MRYR belonged to the slope-climbing types, included 37.38% belonged to the high-slope-climbing types. (4) The regional population density and economic development level were closely associated with regional urban construction land area variability. (5) The climbing process of regional urban construction can effectively alleviate farmland encroachment and pressure on the regional ecological environment. The urban expansion of the metropolitan distribution areas in the Plain region (such as Xi'an, Taiyuan, etc.) had a more significant impact on the local carbon storage."

Wait, this looks like it's already in English. Let me re-read the prompt. The user says "Translate from Simplified Chinese to English". But the text provided is already in English. Let me check if this is a test or if

Full Text

Unveiling Spatial Heterogeneity, Driving Mechanisms, and Environmental Impacts of Urban Slope Climbing Across Varied Landform Types: Insights from the Middle Reaches of the Yellow River

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Abstract

Urbanization research is of great significance for the sustainable utilization of regional land resources and ecological environmental protection. In the middle reaches of the Yellow River (MRYR), the expansion processes and driving factors of urban construction land at different scales remain unclear. This study explored the distribution patterns of urban construction land across different slope gradients at multiple scales and analyzed their influencing factors. The main findings are as follows: (1) Significant expansion of urban construction land occurred in the MRYR over the past 20 years, with spatial heterogeneity observed in regional urban construction land expansion processes among different geomorphic regions. (2) Urban construction land in the MRYR expanded vertically into areas with slopes $>5^\circ$, particularly during 2005-2010. Notable slope climbing of urban construction land was observed in the loess hilly-gully

and rocky mountain areas. (3) 68.45% of counties in the MRYR belonged to slope-climbing types, with 37.38% classified as high-slope-climbing types. (4) Regional population density and economic development level were closely associated with variability in regional urban construction land area. (5) The climbing process of regional urban construction can effectively alleviate farmland encroachment and reduce pressure on the regional ecological environment. Urban expansion in metropolitan distribution areas within the plain region (such as Xi'an, Taiyuan, etc.) had a more significant impact on local carbon storage.

Keywords: Urban expansion; Temporal and spatial distribution; Slope climbing; Driving factors

1. Introduction

Urbanization affects the evolution of land spatial patterns and functions, exerting significant impacts on regional ecosystem stability, food security, and carbon emissions [?]. In recent years, China's rapid urbanization has intensified the supply-demand contradiction of available land resources [?], causing changes in surface water and thermal environments and placing enormous pressure on regional ecosystems [?, ?], while also posing threats to regional food security [?]. Furthermore, land use changes driven by urbanization development have caused substantial losses in terrestrial ecosystem carbon storage, significantly impacting the terrestrial ecosystem carbon cycle, particularly in ecologically fragile regions [?]. Systematic and in-depth analysis of urbanization processes and the development and evolution of urban construction land is crucial for achieving intensive land resource utilization and high-quality regional development, and holds great significance for sustainable regional economic development, ecosystem stability, food security, and achieving dual carbon targets [?].

Urban land expansion primarily occurs in two forms: horizontal expansion and vertical growth [?]. Previous researchers have conducted extensive studies on the spatial and temporal distribution patterns of construction land [?], landscape evolution [?], driving factors [?], and simulation prediction [?] related to regional urban horizontal expansion. These studies have identified a changing pattern of "extension enhancement-deceleration enhancement-stability and unchanged" in urban horizontal expansion, which is mainly influenced by factors such as urban development planning and policies, regional population size, economic development level, natural environment, and transportation [?]. Some studies have also noted that rapid urban expansion leads to landscape fragmentation and spatial differences in agglomeration, which exacerbates the complexity of regional landscape morphology [?], changes the regional water and thermal environment, and places certain pressure on regional ecosystem stability and food security [?]. Building on this foundation, some researchers have simulated future urban expansion processes using methods such as Cellular Automata and Markov chains, proposing corresponding countermeasures based on simulation results [?]. The aforementioned research has greatly promoted regional urbanization studies and provided guidance and experience for sustainable regional

urbanization development.

In recent years, due to the shortage of land resources available for urban construction, construction land has gradually expanded into relatively higher-slope regions in some parts of the world [?]. This trend is particularly significant in complex terrain areas with substantial slope variations, yet previous studies have devoted little attention to urban slope climbing [?]. As an important form of vertical urban expansion, urban climbing has become a widely concerned issue in the urbanization process of non-plain areas [?]. The slope spectrum, as an important indicator for quantitatively studying urban climbing processes, can quantitatively describe the combined morphological characteristics of slope surfaces across terrain gradients through spectral lines, including terrain slope spectrum curves and construction land slope spectrum curves [?]. In recent years, some scholars have investigated urban slope climbing processes under different land use modes using slope spectra [?]. By constructing the Average Built-up Land Climbing Index (ABCI), researchers have systematically analyzed the changing characteristics and patterns of construction land slope spectra in China during 1990–2018, noting that the climbing phenomenon is significant in the complex terrain of central and western regions, with substantial provincial heterogeneity in the degree of construction land climbing [?]. Additionally, some researchers have explored the climbing processes of construction land in typical cities such as Shenzhen [?], Guiyang [?], and Lanzhou-Xining [?], finding that urban construction land climbing occurred in all these cities, with the scale and degree of urban construction land climbing in the Lanzhou-Xining urban cluster showing a gradually decreasing trend [?]. However, current research on urban expansion based on slope range mostly focuses on urban studies under single landform types (such as valley towns [?], mountain towns [?], low hills and gentle slope settlements [?], etc.), lacking systematic and in-depth research on vertical urban expansion under complex landform environments [?]. Particularly in the middle reaches of the Yellow River (MRYR), where the ecological environment is fragile and the human-land contradiction is acute, the processes and driving factors of urban construction land expansion remain unclear, and the influence of urban expansion on the regional environment and carbon reserves requires further exploration. Furthermore, previous studies on vertical expansion of urban construction land have mainly focused on national [?], urban agglomeration [?], and city scales [?], rarely involving county-scale studies. However, significant spatial heterogeneity exists in the level of urbanization across Chinese counties, especially in the complex terrain of the MRYS [?]. Therefore, research on the vertical expansion of urban construction land from the county level is necessary.

The MRYS is located in a transitional zone between arid and semi-arid regions in China, characterized by complex terrain, an arid climate, and prominent ecological and environmental problems. The region's rich and diverse mineral resources make it China's primary energy production base for coal and other energy sources [?]. Recently, with large-scale coal resource development and rapid regional population growth, the urbanization level in the MRYS has significantly improved, and the contradiction between land resource supply and

demand has intensified [?].

Therefore, this study focuses on urban construction land across different land-forms in the MRYR, systematically analyzing the spatiotemporal distribution patterns of urban construction land on slope gradients at both geomorphic and county scales. The study employs a structural equation model to explore the degree of influence of comprehensive regional environmental factors on urban expansion across different terrains and evaluates the impact of urban expansion on farmland, ecological land, and regional carbon reserves. The results provide a theoretical reference for regional urban construction land planning, sustainable land resource utilization, and alleviation of human-land contradictions.

2.1 Study Area

The MRYR is located approximately between 33°45′–40°11′N and 104°27′–113°39′E, adjacent to the Taihang Mountains to the east, Liupan Mountains to the west, Qinling Mountains to the south, and Yinshan Mountains to the north [?]. The region extends 1,206.4 km with a basin area of 344,000 km², accounting for 43.3% of the Yellow River basin area, and primarily includes six provinces and autonomous regions: Shaanxi, Shanxi, Henan, Gansu, Inner Mongolia, and Ningxia (Fig. 1a [Figure 1: see original paper]). Most areas have a temperate monsoon climate, hot and rainy in summer and cold and dry in winter. Precipitation is concentrated from June to September and is unevenly distributed across different regions [?]. From 2000 to 2020, the average annual precipitation in the region ranged between 400 and 600 mm, and the average annual temperature ranged between 9 and 10°C (Fig. 1b). The MRYR is one of China's most vulnerable areas due to sparse vegetation, apparent terrain cutting, and interaction between wind and water erosion. The region has a long history of agricultural civilization, relatively weak economic foundation, and concentrated population distribution. In recent years, the regional urbanization level has increased rapidly due to population growth driven by mineral resource exploitation. By 2021, the MRYR population exceeded 19.8 million, accounting for 13.96% of China's total population, and the gross regional product was projected at 1,317.928 billion yuan, accounting for 11.52% of national GDP [?].

The MRYR is characterized by complex topography that includes ravines. To further analyze the urbanization process across different geomorphic regions, the study area was divided into five categories according to natural conditions [?]: the northwest sandstorm area (SA), loess hilly-gully area (HGA), loess plateau-hilly area (PHA), plain area (PA), and rocky mountain area (RMA).

2.2 Data Sources

The data used in this study primarily included remote sensing, land use, and meteorological data (Table 1). Impervious surface data were used to reflect changes in urban construction land in the study area [?]. Land use and cover maps of the MRYR for five periods (2000, 2005, 2010, 2015, and

2020) were obtained from the Annual China Land Cover Dataset (CLCD, <https://zenodo.org/records/5816591>) with a resolution of 30 m × 30 m. The primary land categories included cropland, forest, grassland, shrubland, water, snow/ice, impervious surface, barren land, and wetland. According to previous studies, CLCD land use data have relatively high spatial resolution and classification accuracy, meeting research precision requirements [?]. Nighttime lighting data were used to reflect regional economic activities and per-capita income [?]. Nighttime lighting data processing and principles followed previous studies [?], with detailed descriptions provided in Appendix 1. According to the Code for Vertical Planning of Urban and Rural Construction Land (CJJ83-2016), the regional topographic slope spectrum of the MRYR, and considering construction land suitability, this study only analyzed construction land with slopes ≤ 25° [?]. The general framework of this study is shown in Fig. 2 [Figure 2: see original paper].

2.3 Methods

2.3.1 Urban Expansion Spatial Distribution Research Methods

This study conducted spatial analysis of urban expansion using topographic slope spectrum curves and construction land slope spectrum curves [?, ?]. Slope data were rasterized with the five-period land-use data (2000, 2005, 2010, 2015, and 2020), the number of raster cells for each slope interval and the number of regional construction land raster cells were counted at 1° intervals, and then the topographic slope spectrum curves and construction land slope spectrum curves were drawn.

The topographic slope spectrum (land area frequency slope range curves) is a statistical map showing the percentage of land area corresponding to the slope factor in a specific statistical area relative to the total statistical area, which can visually reflect the overall slope distribution of the background land [?]. The construction land slope spectrum (construction land area frequency slope spectrum) is a statistical map showing the percentage of construction land area corresponding to the slope factor in a specific statistical area relative to the total construction land area in the statistical area, which can visually reflect both the overall slope distribution of the background land and the land-use preferences of construction land at different slopes [?].

a. The topographic slope spectrum and the construction land slope spectrum

The topographic slope spectrum (i.e., land area frequency slope spectrum) and the construction land slope spectrum [?] were calculated as follows:

$$P_{t,x} = \frac{\text{Area}_{t,x}}{\text{Area}_t} \times 100\%$$

$$P_{cl,x} = \frac{\text{Area}_{cl,x}}{\text{Area}_{cl}} \times 100\%$$

where $P_{t,x}$ and $P_{cl,x}$ are the topographic slope range and construction land slope range of x raster cells, respectively; $\text{Area}_{t,x}$ and $\text{Area}_{cl,x}$ are the land area and construction land area of x raster cells, respectively; and Area_t and Area_{cl} are the total land area and total construction land area of the study area, respectively.

When $P_{cl,x} = P_{t,x}$, the slope range of construction land and the ground slope range intersect, and the slope at this point is defined as the advantageous slope threshold (T). When $P_{cl,x} > P_{t,x}$, the slope range of construction land with slopes less than T is larger than the terrain slope range, and construction land is mainly distributed in raster areas with slopes less than T at this time (called the advantageous area). Conversely, other cases are defined as the inferior area ($P_{cl,x} < P_{t,x}$).

b. Average built-up land climbing index and upper limited slope

This study used the average built-up land climbing index (ABCI) [?] to quantitatively measure the degree of construction land climbing. The specific calculation formula is as follows:

$$\text{BCI} = \left(\frac{GA_b}{A_b} - \frac{GA_a}{A_a} \right) \times 100\%$$

$$\text{ABCI} = \frac{\text{BCI}}{b - a} \times 100\%$$

where BCI (defined as the proportion of construction land area in the disadvantaged area to the total construction land area in a given period) is the built-up land climbing index from year a to year b ; GA_a and GA_b represent the areas of construction land in the disadvantage area in year a and year b , respectively; A_a and A_b are the total areas of construction land in year a and year b , respectively; ABCI is the average climbing index of construction land from year a to year b . $\text{ABCI} > 0$ indicates that the proportion of construction land in the disadvantaged area increases with time (construction land exhibits climbing expansion). Larger ABCI values indicate stronger climbing capacity of construction land.

The upper limited slope change (ULSC) [?] was calculated to analyze differences in slope maxima over time for different construction land distribution scales. When $\text{ULSC} > 0$, it indicates that construction land is climbing to the disadvantaged area in that period, and larger ULSC values indicate greater climbing capacity of construction land. $\text{ULSC} \leq 0$ indicates that construction land is expanding horizontally in the advantageous area during that time.

2.3.2 Regulation Effect of Terrain on Urban Construction Land Research Method

Structural equation modeling (SEM) is a multivariate statistical method based on a covariance matrix that includes factor and path analyses [?]. It can be used to analyze relationships between latent and observed variables, as well as cause-effect relationships among latent variables. The path coefficient beside the arrow in the SEM plot represents the degree of influence between variables, with coefficients ranging from -1 to 1. Values closer to 1 or -1 indicate stronger relationships between variables, while a coefficient of 0 indicates no relationship. The total effect of one variable on another equals the sum of direct and indirect effects. The direct effect is the path coefficient of the variable pointing directly to the target variable, whereas the indirect effect is the product of path coefficients from the variable to the target variable [?].

In this study, AMOS (Analysis of Moment Structure) in SPSS software was used for SEM analysis, and Pearson correlation analysis was used to analyze significance. Based on SEM, this study explored the impact mechanisms of multiple factors on urban construction land, including temperature (Tem), precipitation (Pre), population density (Pop), nighttime lighting (NTL), normalized vegetation index (NDVI), and potential evapotranspiration (PET), within specific ranges of slope, slope aspect, and altitude.

2.3.3 Carbon Storage Calculation Model

The carbon storage module of the InVEST model was used to analyze carbon storage variation in the MRYR between 2000 and 2020, which classified the carbon density of each land use type into four primary carbon pools: aboveground living biomass (C_{above}), belowground living biomass (C_{below}), soil carbon (C_{soil}), and dead organic matter (C_{dead}).

According to the distribution of land use types in the MRYR, the InVEST model analyzes and calculates the total carbon storage (C_{total}) of various land use types [?]. The specific formulas are as follows:

Based on carbon density and land use data from different regions, the formula for calculating carbon storage for each land use type is:

$$C_i = CD_i \times A_i$$

where CD_i represents the average carbon density of each land use type, and A_i represents the area of that land use. The total carbon storage is the sum of all carbon storage.

In this study, the classification and carbon pool of each land use type were determined by summarizing previous research results [?], as shown in Table 2. Carbon density parameters in this study were corrected (annual average temperature and biomass carbon density were corrected using formulas from

[?] and [?], and regional precipitation factor was corrected from [?]); detailed formulas are described in Appendix 1.

3.1 Overall Characteristics of the Environment, Population, and Economy in the MRYR since 2000

During 2000–2020, relatively small fluctuations in annual mean temperature were observed in the MRYR, with a gradually decreasing trend from southeast to northwest (Fig. 3a [Figure 3: see original paper]). Higher air temperatures were observed in the PA and RMA. Annual precipitation in the MRYR showed a gradually increasing trend, decreasing from southeast to northwest (Fig. 3b). Regional PET displayed a spatial distribution pattern of gradually decreasing from southeast to northwest. From 2000 to 2020, relatively higher NDVI values were observed in the PA and RMA. Overall, vegetation coverage in the study area increased significantly, especially during 2010–2020 (Fig. 3d).

During the study period, the areas of cropland and barren land in the MRYR showed decreasing trends, while the areas of forest, water, and impervious surface showed increasing trends (Fig. 3e). However, regional grassland area did not fluctuate significantly during the study period.

Overall, regional population distribution was dense in the southeastern region and sparse in the northwestern region, with population density gradually increasing in recent years (Fig. 3f). During the study period, the total GDP of the MRYR showed an increasing trend (Fig. 3g). Areas with higher GDP were mainly concentrated in the southern and eastern parts of the MRYR, particularly in the PA and RMA regions.

3.2 Urban Construction Land Expansion Process in the MRYR

3.2.1 Temporal Change of Urban Construction Land Expansion in the MRYR

Urban construction land area in the MRYR showed a remarkable expansion trend over the past two decades (Fig. 4a [Figure 4: see original paper]–d), gradually increasing from $7.3 \times 10^3 \text{ km}^2$ in 2000 to $12.9 \times 10^3 \text{ km}^2$ in 2020. Urban construction land expansion was mainly concentrated in larger cities of the Fenhe and Weihe River basins. Regarding growth rate, the urban construction land expansion rate in the MRYR experienced a “declining–rising–declining” trend during 2000–2020, with a declining trend from 2000 to 2005 and an increasing trend from 2005 to 2010. A lower regional urban construction land area expansion rate was observed after 2010, followed by a relatively stable expansion rate during 2015–2020 (Fig. 4d).

During the study period, urban construction land in each geomorphic zone showed a significant increasing trend (Fig. 5 [Figure 5: see original paper]),

with considerable urban expansion occurring in the SA and HGA regions. With regional coal resource development and population growth, the urbanization level in SA significantly improved, and the area of urban construction land increased substantially (from $0.28 \times 10^3 \text{ km}^2$ in 2000 to $1.18 \times 10^3 \text{ km}^2$ in 2020, with a growth rate of 321%) (Fig. 4). The construction land area in the HGA region doubled over the past 20 years (from $9.2 \times 10^3 \text{ km}^2$ in 2000 to $19.1 \times 10^3 \text{ km}^2$ in 2020), with the fastest growth rate occurring during 2005–2010. The expanded urban construction land area was concentrated in the western and northwestern parts of the region (Fig. 5). Due to flat terrain and concentrated population distribution, most urban construction land in the MRYR is distributed in the PA region. By 2020, the area of urban construction land had expanded to $67.1 \times 10^3 \text{ km}^2$ (from $39.1 \times 10^3 \text{ km}^2$ in 2000), with an overall growth rate of 71.61%. The rate of increase in urban construction land area in the PA region during 2015–2020 displayed a slowing trend. Urban construction land expansion in the PA and RMA was mainly concentrated in areas surrounding original towns.

3.2.2 Vertical Expansion of Urban Construction Land in the Middle Reaches of the Yellow River

Urban construction land in the study area presented a regular distribution across slope gradients from 2000 to 2020 (Fig. 6a [Figure 6: see original paper]), with a skewed distribution and spectral peaks in the slope range of 0° – 2° . Above a 2° slope, the proportion of construction land area gradually decreased and eventually tended to 0. The slope spectrum of construction land intersected with the terrain slope spectrum at a slope of approximately 5° , indicating that regional urban construction land was mainly distributed in regions with slopes below 5° . Urban construction land exhibited a trend of vertical expansion into areas above 5° slopes, with the area increasing by approximately 97% over the past 20 years. The urban construction land area in areas with slopes below 5° in the MRYR decreased from 92.8% in 2000 to 91.09% in 2020.

The variation in the upper limited slope (ULS) of construction land in each geomorphic area also presented spatiotemporal heterogeneity, with obvious fluctuations in ULS values observed in SA regions. The urban construction land ULS value in the SA region showed an apparent downward trend (from 11° in 2000 to 6° in 2020) from 2000–2020, implying that urban construction land in this region gradually expanded toward lower slope regions. Comparing the ULSC of urban construction land in different periods (Fig. 6g), a relatively higher upper limit slope value (above 1°) of urban construction land distribution was observed in the 2000–2005 period and varied weakly for the remaining periods.

Additionally, a significantly rising trend of ABCI was observed in the 2000–2010 period, followed by a sharp downward trend in 2010–2015. Based on the results of regional slope spectrum and upper slope analysis, the peak period of urban construction land slope-climbing and vertical expansion mainly occurred in 2005–2010 in the MRYR and was higher than the average level in China

during the same period [?]. Unlike other regions in China, the vertical urban construction land expansion rate in the MRYR gradually trended downward between 2010 and 2015, which was closely related to the implementation of regional soil and water conservation and vegetation restoration projects after 2010 [?].

Due to differences in geographical environment and urban-rural development stages [?], the distribution and climbing degree of urban construction land in the five geomorphic areas of the MRYR differed (Fig. 6b-f). During the study period, the peak value of the construction land slope spectrum in all geomorphic areas showed a downward trend, among which the peak decline in the SA region was the largest (4.21%), followed by those in the RMA (2.32%), PHA (0.61%), PA (0.39%), and HGA regions (0.31%) (Fig. 6). The urban construction land slope spectra in each geomorphic type area presented a smooth inverted “V” curve. Among them, the urban construction land slope spectrum in the SA region was similar to regional topographic slope spectra (Fig. 6). The peak value of the urban construction land slope spectrum in each geomorphic type area of the study area occurred at a 1° slope in 2000–2020, indicating that urban construction land area in the MRYR was mainly distributed in the 1° slope region. The urban construction land slope spectrum in each geomorphic zone presented significant fluctuations in the 0° – 5° slope region, while the slope spectrum curve showed a decreasing trend with increasing slope in the 5° – 25° region (Fig. 6). The proportion of construction land area located below 5° slopes in all geomorphic zones exceeded the average value in China, except for that in the SA region (in 2000) [?].

Fluctuations in ABCI were observed in each geomorphic division during the study period (Fig. 6h). The ABCI in the PHA, PA, and RMA regions showed similar variation characteristics and remained stable. In contrast to other regions, the ABCI of SA displayed a significant upward trend during the study period, with an ABCI value < 0 , indicating that slope-climbing of urban construction land in this region was not evident. Over the past 20 years, ABCI variability in the HGA region demonstrated stronger urban construction land slope-climbing, especially in the 2000–2005 and 2015–2020 periods.

3.2.3 Vertical Expansion of County-Level Urban Construction Land in the MRYR

Counties, as important carriers of new urbanization, represent the most direct operational layer for regional land use and management [?]. The overall level of urbanization in Chinese counties is low and regional differences are significant, especially in the complex terrain of the middle reaches of the Yellow River [?].

Based on ABCI and ULSC calculation results (Fig. 7 [Figure 7: see original paper]), 206 counties in the MRYR were divided into three categories: high-climbing ($ABCI > 0$ and $ULSC > 0$), low-climbing ($ABCI > 0$ and $ULSC < 0$), or $ABCI \leq 0$ and $ULSC > 0$, and horizontal expansion types ($ABCI \leq 0$ and $ULSC < 0$).

$ULSC \leq 0$). The number of climbing counties in the study area (141) accounted for 68.45% of the total number of counties in the MRYR (37.38% and 31.07% for high- and low-climbing types, respectively) during 2000–2020. The largest proportion of hill-climbing counties was in the RMA region (89.19%), whereas the lowest proportion was in the PHA region (37.04%). Typical high-climbing counties included Jincheng in the RMA region, Lingshi in the PA region, and Loufan County in the HGA region, among which Jincheng had the highest ABCI (1.74%). Low-climbing counties included Baode in the HGA region, Wenxi in the PA region, and Uxin Banner in the SA region (Fig. 7). Horizontally expanding counties were mainly concentrated in Xi County in the HGA region, Jingchuan in the PHA region, and Heshun in the RMA region.

The increasing degree of county urban construction land in the MRYR showed significant spatiotemporal heterogeneity (Fig. 7). Due to regional economic development and mineral resource exploitation [?], higher urban construction land slope-climbing was evident in the SA region from 2000 to 2005. Although flat land resources in the PA region were relatively abundant, construction land in this region gradually expanded toward higher-slope areas due to regional economic development and population survival needs [?]. In the RMA region, the implementation of pilot projects for developing unused land, such as low-slope hilly land, resulted in significant slope-climbing of regional urban construction land [?].

Using the natural breaks method as a basis, BCI values were classified into four categories: high, medium, low, and none (Fig. 7e), with 9, 33, 86, and 78 counties, respectively. The slope climbing intensity of construction land was mainly concentrated in the eastern and southern regions, with only 4 counties in the western region having medium or high climbing intensity. Fig. 7f shows that only one county had an average ULS value above 20° from 2000 to 2020, which was Ji County in the HGA. Most counties with an average ULS of 10° – 20° are located in the HGA and PHA, with slight distribution in the RMA areas. Urban construction land in the MRYR during the research period showed a climbing trend at both geomorphological and county scales, but with certain regional differences. The slope climbing trend of urban construction land in the HGA, PHA, PA, and RMA was consistent at both scales, while in the SA, there were certain differences in analysis results between scales. At the geomorphological scale, the phenomenon of construction land climbing in the SA was not obvious, and construction land tended to expand toward low slope areas. At the county level, different towns in the SA exhibited varying degrees of slope climbing at different times. This indicates that regional differences at the county level should be fully considered in land use planning and urban construction in the MRYR, especially in the SA.

3.3 Impact of Environmental and Socio-Economic Factors on Urban Construction Land Expansion

Based on SEM results between regional urban construction land area and environmental-economic elements (Tem, Pre, PET, and NDVI) and economic factors (Pop and NTL), this study systematically discussed the driving mechanism of regional urban construction land expansion at different slopes, slope aspects, and altitudes. Regional environmental and economic factors (except for Tem) significantly influenced urban construction land area variation at different slope gradients ($p < 0.05$), displaying apparent heterogeneity (Fig. 8 [Figure 8: see original paper]). In regions with slopes of 0° - 5° , POP, NTL, PET, and NDVI exhibited significant positive direct effects on regional construction land area variation. The effect of NTL was more significant, whereas that of NDVI was weaker (Fig. 8a). This result indicated that the urban expansion process on low slopes was controlled by many factors, among which economic development was the dominant factor. In regions within the 5° - 10° slope range, only NTL significantly affected urban construction land area ($p < 0.05$) (Fig. 8b), further proving that economic development is an important factor driving the vertical expansion of regional construction land. The positive influence of PET on urban construction land area change became increasingly significant with increasing regional slope, with PET path coefficients for 10° - 15° and 15° - 20° slopes of 0.41 and 0.44, respectively (Fig. 8c-d). For regions within the 20° - 25° slope range, the effect generated by Pre gradually became more evident ($p < 0.05$), and the effects of regional Pop and NDVI on urban construction land changed from positive to negative (Fig. 8e). Regional climate factors become important limiting factors for the expansion of urban construction land to high slope areas.

In different slope direction gradient regions (Fig. 8f-i), variation in regional Pop had a significant regulatory effect on regional urban construction land area variation, with a considerable effect on the semi-sunny slope region and a weaker effect on the sunny slope region. An effect of regional NTL on urban construction land area variation was observed in different slope gradient regions, except in the sunny slope region. PET and NDVI had significant direct positive effects on regional urban construction land area on both sunny and semi-sunny slopes ($p < 0.05$). The regulatory effects of PET and NDVI gradually weakened from sunny to semi-sunny slopes. The effects of regional Tem and Pre on urban construction land area variation for different slope aspects were weaker. These results indicated that the process of construction land expansion on different slope direction gradients was mainly regulated by demographic factors.

The effect of regional Tem on urban construction land area changed from positive to negative as altitude increased. The effect of Pre on urban construction land area at different altitude gradients was not significant. A significant regulatory effect of regional Pop on urban construction land area variation only appeared in regions with altitudes less than 700 m. For regions with 700-2100 m altitudes, both regional NTL and NDVI displayed significant regulatory effects on regional

urban construction land area ($p < 0.05$), indicating that the expansion process of construction land in this region was mainly controlled by regional economic development level and greening level. At altitudes below 700 m, PET positively affected urban construction land area, whereas a significant negative effect was observed in regions above 700 m altitude.

4.1 Influence of Vertical Expansion of Construction Land on Regional Arable Land in the MRYR

The continuous expansion of urban construction land and the decline in high-quality arable land places great pressure on regional food security [?]. Previous studies have indicated that climbing construction land can effectively alleviate farmland encroachment in fragile areas, which is of great significance for protecting high-quality arable land resources [?]. In the present study, the impact of urban construction land slope climbing on regional arable land was further investigated by analyzing the area of urban construction land encroaching on flat arable land (arable land with slope $\leq 2^\circ$ was defined as flat arable land [?]) resources in the MRYR (Fig. 9a [Figure 9 : see original paper]). During 2000–2020, the proportion of flat arable land occupied by regional urban construction land climbing areas fluctuated significantly, with a larger proportion (50.77%) of cropland was converted to other land use types, of which 16.48% was transferred to construction land, and the transferred area from cropland to construction land was 5,040.0 km². Regarding construction land, about 5,835.20 km² was converted from other land use types, of which 86.37% came from cropland. The regional land use transfer matrix results further clarified that the expansion of urban construction land poses a threat to regional food security.

The proportion of urban construction land encroachment on flat arable land in horizontally expanding areas was relatively small (3.73%) during 2005–2010. A significant increasing trend was observed in the 2010–2015 period, followed by a downward trend in 2015–2020. Compared with climbing areas, construction land encroachment on fragile farmland was not significant in horizontal expansion areas.

4.2 Impact of Construction Land Climbing on Ecological Land Use

The occupation of existing ecological land during urban expansion not only reduces living environment quality but also easily triggers regional ecological environmental problems. Following previous study [?], we defined regional forest, grassland, and wetland with slopes $\leq 2^\circ$ as flat ecological land in this study. The current study revealed the impact of urban construction land expansion on regional ecological land by analyzing the area of urban construction land encroaching on flat ecological land in the study area during 2000–2020 (Fig. 9). The results showed a significant downward trend in the proportion of urban construction land encroaching on flat ecological land in high-climbing areas from

2000 to 2015. The lowest proportion of urban construction land occupying fragile ecological land in high-climbing areas was observed in 2015 (7.46%). The trend in the proportion of urban construction land encroaching on flat ecological land in low-climbing areas was similar to that in high-climbing areas.

In horizontal expansion areas, the proportion of flat ecological land occupied by urban construction land was higher than that in the other two areas (high- and low-climbing areas) during the study period, exhibiting a significant upward trend during 2000–2015 and a slightly decreasing trend during 2015–2020. Overall, the proportion of urban construction land encroaching on flat ecological land during slope climbing was lower than that in horizontal expansion areas, indicating that urban construction land slope climbing can effectively alleviate construction land encroachment on flat ecological land.

4.3 Effect of Construction Land Expansion on Regional Carbon Storage in the MRYR

The spatial and temporal distribution of carbon reserves in the study area over the past 20 years was calculated based on the InVEST model. During 2000–2020, carbon storage in the MRYR increased from $3,380.00 \times 10^6$ t to $3,421.30 \times 10^6$ t, with total carbon storage increasing by 27.3×10^6 t. The spatial heterogeneity of regional carbon reserves was also obvious. Lower carbon reserves were concentrated in the SA, urban areas of the PA, and the RMA, while higher carbon reserves were mainly concentrated in forest areas of the central, eastern, and southern MRYR.

The carbon storage per unit area of each land use type in the MRYR was ranked as follows: forest ($12,255 \text{ t} \cdot \text{km}^{-2}$) > grassland ($10,161 \text{ t} \cdot \text{km}^{-2}$) > cropland ($8,805 \text{ t} \cdot \text{km}^{-2}$) > construction land ($6,530 \text{ t} \cdot \text{km}^{-2}$) > barren land ($2,634 \text{ t} \cdot \text{km}^{-2}$) > water ($1,163 \text{ t} \cdot \text{km}^{-2}$). From 2000 to 2010, the carbon stocks of forest, grassland, water, and construction land increased by 49.7×10^6 t, 50.5×10^6 t, 39.1×10^6 t, and 18.3×10^6 t, respectively, while the carbon stocks of cropland and barren land decreased by 84.9×10^6 t and 6.7×10^6 t, respectively. Among various land use types in the MRYR, grassland had the largest carbon storage, accounting for 39.51% of total carbon storage, followed by cropland and forest, accounting for 29.65% and 28.2% of total MRYR carbon storage in 2020. Construction land, barren land, and water had relatively smaller carbon storage, accounting for only 2.53%, 0.07%, and 0.05% of total carbon storage in the MRYR.

Regarding different landforms, carbon storage in the HGA presented the relatively highest value ($1,167.1 \times 10^6$ t in 2020), followed by the PHA (exceeding $1,070 \times 10^6$ t in 2020). During the past 20 years, carbon storage in the SA, HGA, and PHA areas displayed continuous growth trends. However, carbon storage in the RMA presented fluctuating variation, with a decreasing trend from 2000 to 2010 and an increasing trend from 2010 to 2020. Carbon storage in the PA showed a decreasing trend over the past 20 years, decreasing to 581.1

$\times 10^6$ t.

Significant spatial heterogeneity occurred in the influence of urban expansion on regional carbon storage (Fig. 10 [Figure 10: see original paper] g-k). The urban expansion process in the PA had the most significant impact on regional carbon storage. Due to the expansion of urban construction land, carbon storage in the PA decreased by 6.7×10^6 t during 2000–2020. A similar significant influence of urban expansion on regional carbon storage variation was also observed in the RMA. Urban expansion in the SA was relatively weak, leading to relatively weak influence on regional carbon storage variation. At the county scale (Fig. 10), urban expansion in metropolitan distribution areas in the PA (such as Xi' an, Taiyuan, etc.) had a more significant impact on local carbon storage, among which urban expansion in Xi' an led to a decrease in its regional carbon storage by 0.58×10^6 t over the past 20 years. Only three counties displayed an increasing trend in carbon storage during 2000–2020, namely Yonghe County (0.007×10^6 t), Daning County (0.005×10^6 t), and Baode County (0.002×10^6 t).

4.4 Comparison with Existing Research and Outlook for Future Research

Urban expansion is characterized by the sustained interaction between vertical and horizontal growth [?]. However, existing studies have paid much less attention to the slope-climbing phenomenon of construction land in the vertical dimension than to the horizontal expansion of construction land, especially in complex landform regions [?]. Therefore, we comprehensively explored the vertical slope-climbing characteristics of urban construction land across complex landforms at two spatial scales, conducting the first fine classification-scale study of regional construction land in the MRYR, thereby compensating for shortcomings in existing research. In addition, previous studies [?] have pointed out that relatively high-resolution long-time-series LUCC products (with resolution greater than or equal to 30 m) can effectively suppress analytical errors in the evolution of spatiotemporal patterns of vertical urban expansion. In this study, we selected a long series of land use data with a resolution of $30 \text{ m} \times 30 \text{ m}$ to best reveal the evolutionary characteristics of urban construction land across complex landforms while reducing analytical error caused by low accuracy of LUCC products.

In this study, the horizontal expansion and vertical slope climbing of urban construction land in the MRYR coexisted and displayed obvious spatial heterogeneity, which is similar to results from existing hotspot studies (such as Guiyang, Shenzhen, and the Yangtze River urban agglomeration) and studies in other regions of the Yellow River basin (such as Lanzhou-Xining) [?]. It is worth noting that the proportion of construction land area located below 5° slopes in most geomorphic zones of the MRYR exceeded the average value in China, indicating that the horizontal urban expansion process in the area is in a stage of rapid development.

Additionally, gradual urban construction land expansion to high-slope regions and the slope-climbing phenomenon were observed in areas above 5° slopes, especially in the HGA and RMA regions during the study period. Large-scale mineral development, GDP growth, population growth, and limited flat land resources were potential reasons for the vertical expansion of urban construction land in this region [?]. Therefore, scientific and effective spatial planning and tailored development models are essential for regional sustainable urban development [?]. In addition, some regulatory measures are also necessary for areas where the construction land slope-climbing phenomenon was obvious and occupied more ecological land.

In this study, we only examined the horizontal expansion and vertical slope-spectrum characteristics, gradient effects, and driving factors of construction land, and discussed the influence of vertical expansion of construction land on regional arable land, ecological space, and carbon storage. In the future, we plan to conduct long-time-series research, and more highly detailed studies of the evolutionary characteristics of construction land using higher-spatial-resolution and higher-precision data are needed. In addition, we should consider more variables in quantifying the influence factors of climbing construction land (such as government policies, living customs, and historic preservation) and make suggestions for the high-quality development of the MRYS, contributing wisdom to the high-quality protection of the Yellow River basin.

5. Conclusions

Based on data of urban construction land in different geomorphic areas in the MRYS and topographic and construction land slope spectra, this study analyzed the spatial and temporal distribution patterns of urban construction land at different scales, especially at the county scale. The structural equation model was used to analyze influencing factors of regional urban construction land area change under different terrain and geomorphic conditions. The study found:

- During the research period, significant spatial heterogeneity was observed in the spatial distribution of natural factors, climate, economy, and other factors in the MRYS. A superior natural environment was observed in the southeast and plain valleys, which had concentrated population distribution and improved economic development. The expansion of urban construction land in the MRYS increased significantly since 2000, with expansion areas mainly concentrated in the Fen and Wei River basins and the most significant expansion occurring in 2005–2010.
- Significant horizontal expansion of urban construction land was observed in the SA and HGA regions. Urban construction land in the MRYS vertically expanded into areas above 5° slopes, especially during 2005–2010.
- The slope spectrum of urban construction land in each geomorphic type area presented a smooth inverted “V” curve, with obvious urban construc-

tion land slope-climbing appearing in HGA and RMA.

- During 2000–2020, 68.45% of the total number of counties in the MRYR were climbing counties, of which 37.38% were high-climbing counties. A higher proportion of climbing counties was located in the RMA region, whereas a lower proportion appeared in the HGA region.
- Regional population density and economic development levels strongly influenced urban construction land area variability. The influence of natural environment and socio-economic factors on urban construction land variability displayed gradient variation with regional slope, slope aspect, and altitude.
- The urban expansion process in slope-climbing areas poses a threat to regional food security. However, the regional ecological environment of climbing urban construction land improved significantly; therefore, urban construction land slope-climbing somewhat alleviates the ecological security pressure exerted by urban expansion. Urban expansion in metropolitan distribution areas in the PA (such as Xi'an, Taiyuan, etc.) had a more significant impact on local carbon storage.

Author Contributions

SUN Congjian: Conceptualization, methodology, validation, resources, writing—review and editing, project administration, funding acquisition.

CONG Jiamin: Conceptualization, software, validation, investigation, writing—original draft, writing—review and editing, visualization.

CHEN Wei: Validation, formal analysis, data curation, supervision.

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Ethics Declaration

Availability of Data/Materials: The data generated during this study are available.

Conflict of Interest: The authors declare no conflict of interest.

References

References section remains unchanged from the original text.

Appendix 1

1. Nighttime Light Data Processing Method

The nighttime lighting data processing and principles are referenced from [?, ?] and [?, ?]. The details are as follows.

a. DMSP/OLS data preprocessing

1. **Data extraction:** DMSP/OLS NTL data were extracted from China' s administrative boundaries using a mask.
2. **Mutual correction:** The abnormal fluctuation in pixel DN values of multi-sensor images was the main reason for data discontinuity. Mutual correction was performed between sensors to improve image continuity. According to [?], a unary quadratic equation was selected to establish the correction model, as follows:

$$DN_c = aDN^2 + bDN + c$$

where DN and DN_c represent the grey values of pixels before and after correction, respectively, and a , b , and c are regression parameters.

3. **Intra-year fusion:** Due to pixel DN value variations at identical locations within multi-sensor images of the corresponding year and the presence of atypical fluctuations, image-to-image continuity correction was imperative. Using the formula below, image data obtained from distinct sensors were corrected, resulting in unique data for each year from 2000 to 2013:

$$DN(n, i) = \begin{cases} \frac{DN(n, i)_x + DN(n, i)_y}{2}, & \text{if } DN(n, i)_x \cdot DN(n, i)_y \neq 0 \\ 0, & \text{else} \end{cases}$$

where $DN(n, i)_x$ and $DN(n, i)_y$ represent the DN values of the i th pixel from sensors x and y , respectively, in the n th year after correction according to the formula above, and $DN(n, i)$ represents the corrected DN value of the pixel ($n = 2000, 2001, \dots, 2007$).

4. **Temporal series correction:** Based on China' s developmental status, NTL is in an enhanced state. Therefore, assuming a consistently increasing trend in pixel DN values, the DN value of the next year will be higher than that of the previous year, and DN values of missing or unstable pixels will be replaced with zero. Based on this assumption, the formula for correcting multi-year image data acquired by multiple sensors is:

$$DN(n, i) = \begin{cases} DN(n-1, i), & \text{if } DN(n-1, i) > DN(n, i) \\ DN(n+1, i), & \text{if } DN(n+1, i) > DN(n, i) \\ 0, & \text{otherwise} \end{cases}$$

where $DN(n-1, i)$, $DN(n, i)$, and $DN(n+1, i)$ represent the DN values of pixel i in the images for years $n-1$, n , and $n+1$, respectively ($n = 2000, 2001, \dots, 2013$). By applying the aforementioned data correction, we obtained a corrected DMSP/OLS NTL dataset for China from 2000 to 2013.

b. NPP/VIIRS data preprocessing

1. **Annual image synthesis and cropping:** Monthly NPP/VIIRS NTL data on a global scale between 2012 and 2020 were averaged annually. The annual composite data were extracted from China's administrative boundaries using a mask.
2. **Image correction:** Following previous studies [?, ?], radiance values lower than $0.3 \times 10^{-9} \text{ W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ were regarded as noise and assigned a value of 0 to eliminate adverse effects of background noise. Additionally, logarithmic transformation was adopted to suppress sharp changes in pixel values in urban core areas, which was necessary to maintain consistency in numerical ranges between NPP/VIIRS and DMSP/OLS images [?, ?]. The formula is:

$$NPP_{\log} = \log(NPP + 1)$$

where NPP represents the original radiance of the NPP/VIIRS image, and $NPP_{\log}$ is the log-transformed radiance. Constant 1 is added to avoid negative values.

By implementing the aforementioned data correction procedures, a rectified NPP/VIIRS NTL dataset encompassing China's geographic extent for 2012–2020 was obtained.

c. DMSP/OLS and NPP/VIIRS data consistency correction

According to [?], the following formula was used to correct the consistency of DMSP/OLS and NPP/VIIRS images:

$$y = A_1 + (A_2 - A_1) \times \left[\frac{(\log x_{01} - \log x)^{h_1} + (\log x_{02} - \log x)^{h_2}}{p} \right]$$

where y is the calibration value after consistency correction of NPP/VIIRS and DMSP/OLS, x is the radiation value of NPP/VIIRS image after logarithmic transformation, and A_1 , A_2 , $\log x_{01}$, $\log x_{02}$, h_1 , h_2 , and p are model parameters. According to [?], the model parameters are: -31.5988, 190.6737, 0.2857, 1.9352, -3.1132, 0.4410, and 0.0290, respectively.

2. Correction Formula of Carbon Density Parameter

Carbon density varies depending on climate, soil properties, and land use, requiring correction. Therefore, the formula from [?] was used as the correction formula for precipitation factor, and formulas from [?] and [?] were used as correction formulas for annual average temperature and biomass carbon density.

$$CS_P = 3.3968 \times P + 3996.1 \quad (R^2 = 0.11)$$

$$CB_P = 6.798e^{0.00541P} \quad (R^2 = 0.70)$$

$$CB_T = 28 \times T + 398 \quad (R^2 = 0.47, P < 0.01)$$

where CS_P is soil carbon density based on annual precipitation ($\text{kg} \cdot \text{m}^{-2}$), CB_P and CB_T are biomass carbon density based on annual precipitation and temperature ($\text{kg} \cdot \text{m}^{-2}$), respectively, P is average annual precipitation (mm), and T is average annual temperature ($^{\circ}\text{C}$).

Soil carbon density and biomass carbon density were calculated for the whole country and the study area, then correction factors were derived according to the following equations. The carbon density for the study area was the product of the national carbon density and the correction factor.

$$K_B = K_{BT} \times K_{BP}$$

$$K_S = \frac{C''_{SP}}{C'_{SP}}$$

where K_{BP} and K_{BT} are correction coefficients of precipitation factor and temperature factor for biomass carbon density, respectively; C'_{BP} and C''_{BP} are biomass carbon density of the study area and national scale obtained from annual precipitation; C'_{BT} and C''_{BT} are biomass carbon density of the study area and national scale based on annual temperature; C'_{SP} and C''_{SP} are soil carbon density of the study area and national scale according to annual temperature; K_B and K_S are correction coefficients of biomass carbon density and soil carbon density, respectively.

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

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