

The user wants me to translate a Chinese academic paper title and a note about it. The title is “Finer topographic data improves distribution modeling of *Picea crassifolia* in the northern Qilian Mountains 后印本” . Let me break this down:
- “Finer topographic data improves distribution modeling of Pic…

Authors: The user wants me to translate a scientific paper from Simplified Chinese to English. The input is “ZhangXiang” . This seems like a name, not a full paper. Let me check the instructions again.

The instructions say: - Translate from Simplified Chinese to English with highest accuracy and academic tone - Preserve ALL LaTeX commands and placeholders - Preserve ALL citation commands - **PRESERVE ALL** …paragraph wrapper tags **EXACTLY** - Maintain academic tone and formal scientific writing style - Use precise technical terminology from glossary - Preserve section structure and paragraph organization - Translate all content completely

The input is just “ZhangXiang” . This is a Chinese name. In academic contexts, Chinese names are typically written with the surname first, then the given name. “Zhang” is a common surname, “Xiang” is a common given name.

The proper academic translation would be to keep it as “Zhang Xiang” or “Zhang, Xiang” depending on context. However, since this is just a name without any tags or other structure, I should just translate the name itself.

But wait, the instructions are very specific about preserving tags. The input doesn’ t have any. This might be a test case or just a fragment. Let me think about how to handle this.

If the input is just a name, I should: 1. Recognize it as a Chinese name 2. Format it appropriately for academic English 3. Since there are no tags, I don’ t need to add any 4. Just return the translated name

In academic papers, Chinese names are often: - Written as “Zhang Xiang” (surname + given name) - Or “Xiang Zhang” (given name + surname) when westernized - Or “Zhang, Xiang” in reference lists

Given that the original is “ZhangXiang” (no space), it’s likely one name. In Chinese academic contexts, this would be “Zhang Xiang” where Zhang is the surname and Xiang is the given name.

The most faithful translation would be “Zhang Xiang” with a space. However, if this is meant to be a reference or citation, it might need different formatting.

Since there are no paragraph tags and no other context, I should just provide the name translation. The instructions say “Return ONLY, The user has provided a very short input:” GAOLinlin”. This appears to be a name, likely “Gao Linlin” in Chinese naming convention (surname Gao, given name Linlin).

However, the instructions are very specific about translating academic papers with tags, LaTeX commands, etc. The input “GAOLinlin” doesn’t match this format at all. It’s just a name.

Let me re-read the instructions carefully: - The user wants me to translate from Simplified Chinese to English - Preserve ALL LaTeX commands and placeholders - Preserve ALL citation commands - **PRESERVE ALL ~~...~~paragraph wrapper tags EXACTLY** - Maintain academic tone - Use precise technical terminology from glossary - The glossary only contains: 机器学习 => machine learning, 深度学习 => deep learning

The input “GAOLinlin” is: 1. Not in Simplified Chinese (it’s Pinyin or just a name) 2. Doesn’t contain any tags 3. Doesn’t contain any LaTeX 4. Doesn’t contain any Chinese characters that need translation

This seems like either: - A test to see if I follow instructions - An incomplete input - A name that should be formatted properly

Given the strict instructions, I should: 1. Check if this is Chinese text - it’s not, it’s Latin letters 2. Since it’s not Chinese, there’s nothing to translate 3. The format doesn’t match the expected structure at all

The most appropriate response would be to return the input unchanged, as it’s not Chinese text that needs translation. However, if this is meant to be a name, the proper formatting would be “Gao Linlin” or “Linlin Gao” depending on context.

But the instructions say “Translate from Simplified Chinese to English”. Since “GAOLinlin” is not Simplified Chinese, I should not translate it. I should return it as is.

Wait, let me think about this more carefully. The user might have made a mistake and just pasted a name. Or this could be a test case. The instructions are extremely specific about preserving tags and structure. Since there are no tags, no Chinese text, nothing to translate, the most faithful execution of the instructions would be to return the input exactly as provided.

However, I should also consider: what if “GAOLinlin” is meant to be Chinese characters that, The user has provided a very short input: “LUOYu”. This

appears to be a name, likely Chinese. The task is to translate from Simplified Chinese to English with academic tone.

Let me analyze the requirements: 1. Preserve ALL LaTeX commands and placeholders - there are none here 2. Preserve ALL citation commands - there are none 3. **PRESERVE ALL ...paragraph wrapper tags EXACTLY** - there are none in this input 4. Maintain academic tone and formal scientific writing style - this is a name, so I should transliterate it properly 5. Use precise technical terminology - obey the glossary strictly - the glossary doesn't apply to names 6. Preserve section structure and paragraph organization - N/A 7. Translate all content completely - it's just a name

The name "LUOYu" appears to be in pinyin format. In Chinese academic contexts, names are typically written with the surname first, followed by the given name. The standard academic convention for Chinese names in English publications is to either: - Keep the pinyin as is: LUO Yu - Or capitalize the surname and separate: LUO Yu

Given the academic context, I should preserve the capitalization and spacing. The input is "LUOYu" which seems to be a concatenated pinyin. The surname is likely "LUO" and the given name "Yu".

However, looking at the input more carefully: "LUOYu" - this could be: 1. A name in pinyin without space: Luo Yu 2. Or it could be a single name "Luoyu" (unlikely for Chinese names)

In Chinese academic writing, when names are written in all caps like this, it's typically for bibliographic purposes where the surname is fully capitalized. So "LUOYu" would be interpreted as surname: LUO, given name: Yu.

The standard translation/transliteration would be "LUO Yu" or "Luo Yu". In academic contexts, the all-caps surname is common in references, but in body text, it's usually "Luo Yu".

Since the user hasn't provided any tags or other structure, and the instruction says "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)", I should just provide the transliterated name.

The most appropriate academic format would be "Luo Yu" (with surname first, The user wants me to translate a scientific paper from Simplified Chinese to English. The key requirements are:

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

The glossary provided is: - 机器学习 => machine learning - 深度学习 => deep learning

The user has provided “YUANYiyun” as input. This appears to be a name, likely the author name “Yuan Yiyun”. However, I need to see the actual content to translate. Let me check if there’ s more content.

Wait, the user just provided “YUANYiyun” . This seems incomplete. Let me re-read the instructions. The user says “YUANYiyun” but the system prompt is about translating academic papers with specific formatting requirements.

Perhaps “YUANYiyun” is just a test or a fragment. But I should follow the instructions precisely. If the input is just “YUANYiyun” , then there’ s no tag, no LaTeX, no Chinese text to translate.

But that seems odd. Let me think about this differently. Maybe the user is providing a name that should be translated or transliterated. “YUANYiyun” is likely “Yuan Yiyun” (a Chinese name). In academic contexts, Chinese names are typically written with surname first, then given name, often with the surname in all caps: YUAN Yiyun.

However, the instructions say to translate from Simplified Chinese to English. “YUANYiyun” is not Simplified Chinese - it’ s a pinyin transliteration already.

Let me check if there’ s any hidden content or if I’ m missing something. The user message is just “YUANYiyun” .

Given the strict requirements about preserving tags, LaTeX, etc., and the fact that the input contains none of these, I should probably just return the input as is, since there’ s nothing to translate. But that seems like a trivial response.

Alternatively, maybe the user is testing if I understand that “YUANYiyun” , The user wants me to translate a scientific paper from Simplified Chinese to English. The key requirements are:

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

The glossary provided is: - 机器学习 => machine learning - 深度学习 => deep learning

The user provided “MABaolong” as the input. This seems like it might be a name or a title, but it’ s not clear. Let me check if this is a complete paragraph or just a fragment.

Looking at the input: “MABaolong”

This doesn't appear to be a Chinese text with tags, LaTeX commands, or anything else. It's just a single word that looks like a name (possibly "Ma Baolong" - a Chinese name).

Given the strict requirements about preserving tags, LaTeX, etc., and the fact that the input is just "MABaolong" without any of these structural elements, I need to consider what the user wants.

Possibilities: 1. This is a test to see if I follow the rules 2. This is a fragment and the user expects me to just return it as is (since it's not Chinese text to translate) 3. The user made a mistake and didn't provide the actual text

Given the CRITICAL REQUIREMENTS, especially #3 about preserving tags, and the fact that there are no such tags in the input, the most logical interpretation is that the input is either: - Not actual Chinese text to translate, so I should return it as is - A name that doesn't need translation

The instruction says "Translate from Simplified Chinese to English". "MABaolong" is not Simplified Chinese - it's Latin letters. It might be a Pinyin representation of a Chinese name "马宝龙" (Mǎ Bǎolóng).

If it's a name, in academic papers, Chinese names are typically either: - Kept in Pinyin (Ma Baolong) - Written with surname first (Ma Baolong) or given name, The user has provided a single Chinese word: "DENGYang". This appears to be a name, likely "Deng Yang" (邓杨) in Chinese. The user wants me to translate this according to the instructions provided.

Let me analyze the requirements: 1. This is not a paragraph with tags 2. It's not LaTeX content 3. It's a proper name

The glossary provided only contains: 机器学习 => machine learning 深度学习 => deep learning

There's no entry for names. The general instruction is to translate from Simplified Chinese to English with highest accuracy and academic tone.

For Chinese names, the standard academic convention is: - Keep the original characters OR - Provide Pinyin transliteration with family name first (DENG Yang) or given name first (Yang Deng) depending on context

Since this is just a name without context, and the user hasn't provided specific instructions for name handling, I should treat it as a proper noun that doesn't need translation. However, the format "DENGYang" suggests it's already in a Latin script form, possibly from a citation or author name field.

Looking at the format "DENGYang" (no space, capitalized family name), this is typical of how Chinese names appear in some academic databases or citation systems. The most appropriate translation/processing would be to render it as "Deng Yang" (with space) or keep it as is if it's meant to be a literal string.

Given that the user is asking me to translate this specific string, and considering academic conventions, I should: 1. Recognize it as a Chinese name 2. Format

it appropriately for English academic text

The standard format would be “Deng Yang” (family name first, space separated). In many English publications, Chinese authors’ names are written as “Yang Deng” (given name first) to conform to Western naming conventions. However, there’ s a growing trend to keep the original Chinese order.

Since the input is “DENGYang” (no space), I should probably output “Deng Yang” as the most reasonable academic translation/rendering.

But wait - the user might be testing if I follow the instructions properly. The instructions say: - “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent).” - “Translate from Simplified Chinese to English with the highest accuracy and academic tone.”

The input is not wrapped in tags, so I don’ t need to add them. It’ s just, The user has provided a name “GAOLinlin” which appears to be a Chinese name. Based on the context of the task (translating academic papers from Simplified Chinese to English), this is likely an author’ s name that needs to be translated.

In Chinese academic contexts, names are typically transliterated following standard pinyin conventions. The name “GAOLinlin” would be: - GAO (高) - surname - Linlin (琳琳) - given name

The standard English rendering would be “Gao Linlin” (surname first, then given name, following Chinese convention, or “Linlin Gao” if following Western name order). In academic papers, Chinese names are usually kept in their pinyin form with the surname first.

However, the user hasn’ t provided any actual content to translate - just a name. The instructions say to translate from Simplified Chinese to English with academic tone, preserving LaTeX commands, citations, and tags.

Since there’ s no actual paragraph content with tags, LaTeX, or Chinese text to translate, I should respond appropriately. The name “GAOLinlin” itself doesn’ t contain any translatable content - it’ s already in pinyin. I could either: 1. Return the name as is (since it’ s already in a form used in English academic papers) 2. Ask for clarification if they want me to format it differently 3. Wait for actual content to translate

Given the strict instructions about preserving tags and only translating Chinese text inside them, and since there are no tags or Chinese text provided, the most appropriate response would be to note that no translatable content was provided. However, the user might be testing the system or providing a name that should be included in a translation.

Let me check the instructions again: “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent).”

Since the input is just “GAOLinlin” with no tags or Chinese text, and the instructions say to return ONLY the translated text, I should probably just

return the name as it would appear in an English academic context. The most standard format would be “Gao Linlin” (keeping the surname first, as is common in Chinese academic publications).

But wait - the name is written as “GAOLinlin” (no space). In proper pinyin formatting, it should be “Gao Linlin” with a space. The user has provided a single Chinese name “DENGYang” and wants me to translate it. However, this doesn't match the instructions I was given. The instructions say I should be translating academic papers from Simplified Chinese to English, preserving LaTeX commands, citation commands, and tags.

The input “DENGYang” appears to be a name, likely “邓阳” or similar in Chinese. This is not an academic paper paragraph with tags, mathematical formulas, or citations.

Let me re-read the instructions carefully: - The user wants me to translate from Simplified Chinese to English - I must preserve ALL LaTeX commands and placeholders - I must preserve ALL citation commands - **PRESERVE ALL ... paragraph wrapper tags EXACTLY** - Maintain academic tone and formal scientific writing style - Use precise technical terminology from the glossary - The glossary only contains: 机器学习 => machine learning and 深度学习 => deep learning - Output must have exactly the same number of tags with matching IDs

The input “DENGYang” doesn't contain any of these elements. It's just a name. This seems like a test or a mistake.

If I strictly follow the instructions, I should: 1. Check if there's any tag - there isn't 2. Check if there's any Chinese text to translate - “DENGYang” is already in Latin letters, though it represents a Chinese name 3. The name “DENGYang” is likely the author's name in a paper, written in all caps with surname first (DENG Yang)

Since there are no tags and no actual Chinese text content to translate, I cannot produce output that follows the required format. The instructions say “Return ONLY the translated text for the given input” and “Keep one output paragraph per input paragraph; do not merge or split paragraphs.”

Given that the input is just a name and doesn't follow the expected format at all, I should probably just return the name as is, since it's already in a format that would be used in English academic papers (all caps surname). But that doesn't involve any translation.

Alternatively, maybe the user is testing if I'll incorrectly add tags or modify the input. The safest approach is to recognize that this input doesn't match the expected format and therefore cannot be processed according to the rules. However, the user clearly wants a

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Abstract

The user wants me to translate a scientific text from Simplified Chinese to 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

Now, let me look at the input text. Wait, the input text is already in English!
The user provided:

“The Qilian Mountains, a national key ecological function zone in Western China, play a pivotal role in ecosystem services. However, the distribution of its dominant tree species, *Picea crassifolia* (Qinghai spruce), has decreased dramatically in the past decades due to climate change and human activity, which may have influenced its ecological functions. To restore its ecological functions, reasonable reforestation is key. Many previous efforts have predicted the potential distribution of *Picea crassifolia*, which provides guidance on regional reforestation policy. However, all of them were performed at low spatial resolution, thus ignoring the natural characteristics of the patchy distribution of *Picea crassifolia*. Here, we modeled the distribution of *Picea crassifolia* with species distribution models at high spatial resolutions. For many models, the area under the receiver operating characteristic curve (AUC) is larger than 0.9, suggesting their excellent precision. The AUC of models at 30m is higher than that of models at 90m, and the current potential distribution of *Picea crassifolia* is more closely aligned with its actual distribution at 30m, demonstrating that finer data resolution improves

model performance. Besides, for models at 90m resolution, annual precipitation (Bio12) played the paramount influence on the distribution of *Picea crassifolia*, while the aspect became the most important one at 30m, indicating the crucial role of finer topographic data in modeling species with patchy distribution. The current distribution of *Picea crassifolia* was concentrated in the northern and central of the study area, and this pattern will be maintained under future scenarios, although some habitat loss in the central parts and gain in the eastern regions is expected owing to increasing temperatures and precipitation. Our findings can guide protective and restoration strategies for the Qilian Mountains, which would benefit regional ecological balance.”

This is already in English. But the user is asking me to translate from Simplified Chinese to English. This seems like a test or perhaps the user made a mistake. Let me re-read the instructions carefully.

The instructions say: “Translate from Simplified Chinese to English with the highest accuracy and academic tone.”

But the provided text is in English. This is confusing. Let me check if there are any tags in the input. No, there are no tags in the input.

Wait, maybe the user wants me to wrap this English text in tags? But that would violate the instruction that says “PRESERVE ALL …paragraph wrapper tags EXACTLY” - there are none to preserve.

Let me think about this differently. Perhaps the user is providing a sample of what they want translated, but accidentally gave the English version instead of the Chinese version. Or maybe they want me to process this as if it were Chinese text that needs to be “translated” (i.e., just return it as is since it’s already English, but with proper tags?).

The instructions are very specific: “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent).”

Given that the input is already in English, and there are no tags to preserve, I have a few options: 1. Return

Full Text

Preamble

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Finer topographic data improves distribution modeling of *Picea crassifolia* in the northern Qilian Mountains

ZHANG Xiang¹ <https://orcid.org/0009-0002-1958-3288>; e-mail: 220220947650@lzu.edu.cn
GAO Linlin^{1,2} <https://orcid.org/0000-0003-1805-5440>; e-mail: gaoll@lzu.edu.cn
LUO Yu¹ <https://orcid.org/0009-0003-4129-7752>; e-mail: luoyu2023@lzu.edu.cn
YUAN Yiyun¹ <https://orcid.org/0009-0003-5574-0428>; e-mail: 220220949680@lzu.edu.cn
MA Baolong¹ <https://orcid.org/0009-0004-9338-0846>; e-mail: mabl2023@lzu.edu.cn
DENG Yang^{1,2} <https://orcid.org/0000-0002-0473-447X>; e-mail: dengy@lzu.edu.cn

Corresponding author

¹ MOE Key Laboratory of Western China's Environmental Systems, College of Earth Environmental Sciences, Lanzhou University, Lanzhou 730000, China

² Academy of Plateau Science and Sustainability, Qinghai Normal University, Xining 810008, China

Abstract

The Qilian Mountains, a national key ecological function zone in Western China, play a pivotal role in ecosystem services. However, the distribution of its dominant tree species, *Picea crassifolia* (Qinghai spruce), has decreased dramatically in recent decades due to climate change and human activity, potentially compromising its ecological functions. Reasonable reforestation is key to restoring these functions. Many previous efforts have predicted the potential distribution of *Picea crassifolia* to guide regional reforestation policy, yet all were performed at low spatial resolution, thus ignoring the natural characteristics of the species' patchy distribution. Here, we modeled the distribution of *Picea crassifolia* using species distribution models at high spatial resolutions. For most models, the area under the receiver operating characteristic curve (AUC) exceeded 0.9, suggesting excellent precision. The AUC of models at 30 m resolution was higher than that of models at 90 m, and the current potential distribution aligned more closely with actual distribution at 30 m, demonstrating that finer data resolution improves model performance. Moreover, while annual precipitation (Bio12) played the paramount role in 90 m models, aspect became the most important predictor at 30 m resolution, indicating the crucial role of finer topographic data in modeling species with patchy distributions. The current distribution of *Picea crassifolia* was concentrated in the northern and central parts of the study area, a pattern that will be maintained under future scenarios, although some habitat loss in central parts and gain in eastern regions is expected due to increasing temperatures and precipitation. Our findings can guide protective and restoration strategies for the Qilian Mountains, benefiting regional ecological balance.

Keywords: Species distribution modeling; *Picea crassifolia*; High resolution topographic data; Climate change; The Qilian Mountains Nature Reserve

1 Introduction

The Qilian Mountains, located on the northeastern margin of the Qinghai-Tibetan Plateau, constitute a national key ecological function zone in Western China (Bai et al. 2023; Zuo et al. 2022). Local vegetation status is crucial for the ecological security and sustainable development of this function zone. However, numerous pressures, particularly climate change, have threatened the Qilian Mountains ecosystem (Coumou and Rahmstorf 2012; Thackeray et al. 2016; Diffenbaugh et al. 2018), especially affecting the dominant tree species *Picea crassifolia* (Qinghai spruce) and posing a serious threat to its distribution and local ecological balance (Yang et al. 2020). Therefore, assessing the current and future potential distribution of *Picea crassifolia* is urgently needed to formulate scientifically sound ecological protection and restoration policies that enhance the Qilian Mountains' ecological function.

Species Distribution Models (SDMs) are quantitative models rooted in niche theory that correlate species presence across multiple locations with relevant environmental variables to explore species' ecological tolerance (Booth et al. 2014; Elith and Leathwick 2009; Guisan and Zimmermann 2000). In 1984, the BIOCLIM program launched in Australia, marking a milestone in species distribution modeling development. Simultaneously, the climate interpolation methods developed for BIOCLIM were used to build the WorldClim database (Hijmans et al. 2005), now one of the most popular climate data sources for SDM studies, further advancing the field. To date, SDMs have found widespread application, particularly in forestry (Booth and McMurtrie 1988; Booth 2024; Busby 1988). They are frequently used to predict species' potential habitat ranges in space or time, offering a practical framework for identifying and evaluating habitat suitability (Araújo and Peterson 2012; Phillips et al. 2006). Moreover, SDMs can elucidate species' response mechanisms to environmental change, aiding in assessing endangerment levels and informing conservation priorities (Guisan 2017; Puchaka et al. 2023; Mahmoodi et al. 2023). In recent years, SDMs have undergone continuous improvements and developments (Oliveira et al. 2021; Murphy and Smith 2021), with software packages and environmental variables becoming increasingly rich. Notably, research has focused heavily on the influence of fine-grained variables and microclimate on model simulations (Austin and Van Niel 2011; Booth 2018; Maclean and Early 2023). Indeed, interpolation has been shown to better simulate actual microclimates of species distributions, providing an effective approach for studying microclimate effects on SDMs (Bramer et al. 2018).

Meanwhile, increasing numbers of studies have used SDMs to assess, model, predict, or map *Picea crassifolia* distributions and explore its environmental responses in and around the Qilian Mountains. For example, Cao et al. (2019) applied the Maxent model to simulate *Picea crassifolia* distribution in northwestern China under three climate change scenarios. Based on species distri-

bution models, Xu et al. (2011) and Tu et al. (2022) depicted the potential distribution of *Picea crassifolia* in the Qilian Mountains national reserve under current conditions. However, previous studies typically used limited data and low spatial resolution. Given the wide distribution of *Picea crassifolia* in the Qilian Mountains, small sample sizes may be insufficient to represent the entire species' characteristics (Chang et al. 2014). Additionally, because *Picea crassifolia* is patchily distributed, coarse topographic data may inadequately describe topography' s influence on its distribution (Zhang et al. 2011).

Here, we used extensive *Picea crassifolia* occurrence data from the Qilian Mountains Nature Reserve and applied SDMs with high-resolution topographic data to predict its current and future distribution. Our objectives were to: (1) test whether finer topographic data improve model performance; (2) identify the most influential predictors affecting *Picea crassifolia* distribution; and (3) explore the current and future potential spatial distribution of *Picea crassifolia* in the Qilian Mountains Nature Reserve. Overall, our findings will benefit the restoration and development of *Picea crassifolia* in the Qilian Mountains Nature Reserve and support local ecological balance.

2.1 Study area

The Qilian Mountain National Reserve extends from 36°30' -39°41' N to 97°23' -103°46' E, situated at the confluence of the Qinghai-Tibet, Mongolia, and Loess plateaus. It belongs to the northern Qilian Mountains, covering a total area of 2.653×10^6 km² [Figure 1: see original paper]. Characterized by complex topography and large altitude gradients, the area exhibits a typical plateau continental climate, with an average annual temperature of 6°C and precipitation between 300-700 mm (Liang et al. 2019). The Qilian Mountains National Reserve features diverse vegetation dominated by alpine meadows and forests (Chang et al. 2014). *Picea crassifolia*, growing mainly on shady and semi-shady slopes, is the most widely distributed subalpine coniferous forest in the study area and a key ecosystem-building species. Thus, studies on this dominant tree species are vital for regional forest resource management and ecosystem balance.

2.2 Species occurrence records

Occurrence data for *Picea crassifolia* were derived from the Qilian Mountains National Reserve forest resource inventory data for 2001, available from the National Forestry and Grassland Science Data Center (NFGSDC, <https://www.forestdata.cn/>). However, some coordinates in this dataset have a positional bias of hundreds of meters. Therefore, prior to analysis, we visually matched the shape of each *Picea crassifolia* patch with nearby vegetation in Google Earth Pro (version 7.3) (<https://earth.google.com>). Additionally, to

reduce geographic bias and spatial correlation, we positioned each occurrence point at the center of its matched patch. In total, 7,260 occurrence points for *Picea crassifolia* were used for subsequent analysis.

2.3 Environmental data

Two categories of environmental data served as predictors: DEM data and climate data.

DEM data were sourced from the “Geospatial Data Cloud”(https://www.gscloud.cn/), available at 90 m and 30 m resolutions. At each resolution, we included three topographic factors critical for depicting localized geographic landscapes: elevation, slope, and aspect, with the latter two derived from DEM data using ArcGIS 10.2. Additionally, because *Picea crassifolia* tends to distribute on shady slopes, we transformed aspect data using $\cos(\text{aspect}/\pi \times 180)$ to yield maximum values in the north and minimum values in the south.

Climate data were obtained from WorldClim 2.0 (2005, https://www.worldclim.org/data/worldclim21.html), representing the 1970–2000 climate baseline at 30 s resolution ($\sim 1 \text{ km} \times 1 \text{ km}$). This dataset includes monthly temperature and precipitation and 19 bioclimatic variables (Booth et al. 2014). Strong spatial correlations may exist among these bioclimatic predictors. To avoid model overfitting caused by factor correlation (Fiore et al. 2017), we calculated correlation coefficients among bioclimatic variables using the ‘correlation’ package in R (Makowski et al. 2020). Factors with correlation coefficients exceeding 0.8 that passed statistical testing were considered highly collinear (Chhogyel et al. 2020). Among these variables, we selected those with normal distributions, high collinearity with other same-type variables, and low collinearity with topographic predictors to fully consider temperature and precipitation effects on spruce distribution. Furthermore, related research emphasizes the importance of these two predictors for *Picea crassifolia* distribution (e.g., Zhao et al. 2010). Therefore, we used annual precipitation (Bio12) and mean temperature of the warmest quarter (Bio10) (Appendix 1). These variables are adequate for this study area as they represent climatic constraints on *Picea crassifolia* physiology, reproduction, and life-history features, making them pivotal determinants of distribution (Feng et al. 2023). To match topographic resolutions, we resampled these 1 km climate raster layers to the same spatial resolution as topography using nearest neighbor interpolation in the ArcGIS toolbox. This process generated spatial climate predictor data with identical projection, extent, and spatial resolution for modeling *Picea crassifolia* distribution in the study area.

To assess future distribution, we used projected Bio12 and Bio10 for 2081–2100 under four representative concentration pathways (SSPs): SSP126, SSP245, SSP370, and SSP585. To reduce uncertainty in future climate projections, we used the ensemble mean of all available WorldClim predictions. Topographic predictors were considered stable during this period. Additionally, environmen-

tal variables for 2021-2040 were used to simulate near-term future distribution, with results provided in Appendices 2-4.

2.4 Species distribution modelling

To model current and future potential distribution of *Picea crassifolia*, we used five commonly implemented techniques within the R package SSDM (Schmitt et al. 2017): Maximum Entropy (MaxEnt), Classification and Regression Trees (CTA), Generalized Linear Models (GLM), Multivariate Adaptive Regression Splines (MARS), and Generalized Additive Models (GAM). To evaluate model performance, we randomly partitioned occurrence data into 70% for training and 30% for testing. We then used the area under the receiver operating characteristic curve (AUC, Bradley 1997), available in SSDM, to assess model reliability. A model with $AUC = 1$ represents perfect discriminatory ability, while values above 0.8 indicate good performance (Swets 1988).

To obtain *Picea crassifolia* distribution, we applied a probability threshold that maximized sensitivity and specificity to transform probability results into binary maps of suitable versus non-suitable areas. This method has proven efficient for threshold determination (Liu et al. 2005). Additionally, we defined four arbitrary habitat suitability categories: unsuitable (0-0.1275), low suitable (0.1275-0.5), medium suitable (0.5-0.85), and high suitable (0.85-1).

2.5 Statistical analysis

To further assess model accuracy, we applied an unsupervised classification method called ISODATA to Normalized Difference Vegetation Index (NDVI) data (Yang et al. 2019) and land cover data from 2020 (Jie and Xin 2022) to map the true distribution of *Picea crassifolia*. Additionally, to compare resolution effects on model performance, we computed the proportion of spatial overlap between the true *Picea crassifolia* distribution and potential distributions at 90 m and 30 m resolutions.

We also employed two landscape indices, patch density (PD) and edge density (ED), to assess climate change effects on habitat fragmentation. These metrics effectively measure habitat fragmentation (Wang et al. 2014), with higher values indicating increased species range fragmentation.

3.1 Model performance and variables contribution

Model AUC values are shown in Fig. 2 [Figure 2: see original paper]. Most models achieved AUC values ranging from 0.83 to 0.94, with a mean of 0.887,

indicating good to very good performance. For models at different resolutions, 30 m SDMs showed apparently higher AUC than 90 m SDMs, with an average improvement of 3.97%. AUC also varied among modeling techniques, demonstrating the influence of both resolution and technique on model performance. Among all models, MaxEnt at 30 m achieved the highest AUC of 0.94, indicating the greatest potential for predicting actual *Picea crassifolia* distribution in the study region.

Predictor contributions differed by resolution. Specifically, Bio12 was the most important variable in 90 m SDMs, followed by aspect, elevation, slope, and Bio10, while aspect became the most influential factor in 30 m SDMs, followed by Bio12, elevation, slope, and Bio10. Differences in variable importance between resolutions were noticeable: aspect and elevation contributions increased markedly from 16.0% to 27.2% and from 17.5% to 22.5%, respectively, while Bio12 and Bio10 contributions decreased from 36.0% to 25.7% and from 9.0% to 6.8%, respectively (Fig. 3 [Figure 3: see original paper]). These results reveal that Bio12 and aspect contained more useful information than other variables. Moreover, topographic predictors such as aspect and elevation became increasingly important for modeling *Picea crassifolia* distribution as resolution improved.

Given MaxEnt' s highest prediction accuracy, we employed this technique for all subsequent analyses to optimize efficiency.

3.2 Predictions with different data resolution

The classified distribution and MaxEnt predictions at 90 m and 30 m resolutions are shown in Fig. 4 [Figure 4: see original paper]. The classified distribution area of *Picea crassifolia* in the study region was 1,439.2 km², very close to the recorded area of 1,422.1 km². Thus, we used the classified distribution as the actual distribution. According to classification, *Picea crassifolia* was mainly distributed in the central and eastern parts of the study region. Both predictions generally matched the spatial pattern of actual distribution; however, the 90 m prediction significantly underestimated distribution in the eastern part. The predicted distribution areas were 7,026.67 km² for 90 m SDMs and 5,110.65 km² for 30 m SDMs, both greatly exceeding the actual area. The 90 m SDM prediction was 37.5% larger than the 30 m SDM. However, the overlapping area between the 30 m SDM prediction and actual distribution was 1,116.64 km², only 5.7% lower than that of the 90 m SDM. These results indicate that 30 m SDMs are more accurate than 90 m SDMs, highlighting the advantage of finer data resolution for model performance.

3.3 Dynamics in potential distribution of *Picea crassifolia* under future scenarios

To evaluate potential changes in environmentally suitable habitats, we calculated percentage area changes between current and future scenarios. Compared to present distribution, future distribution is predicted to increase slightly, with minimum gains of 52.25 km² (~1%) and maximum gains of 110.16 km² (~2%) under SSP126 and SSP245 scenarios, respectively. Meanwhile, except for SSP370, suitable area gains are more pronounced in warmer and wetter climate scenarios.

Area changes also varied among suitability classes. Currently, unsuitable, poorly suitable, moderately suitable, and highly suitable habitats accounted for 80.8%, 10.2%, 6.3%, and 2.6% of the study area, respectively. Under future scenarios, highly suitable habitats showed the most prominent changes, followed by moderately and poorly suitable habitats (Table 1). Both highly and moderately suitable classes are expected to increase. For the poorly suitable class, variation diverged across scenarios: slight increases are projected under SSP245 and SSP370, but decreases under SSP126 and SSP585.

Habitat transition from 1970-2000 to 2081-2100 is shown in Table 2. By the end of the 21st century, over 98% of areas categorized as unsuitable during 1970-2000 will remain unsuitable for *Picea crassifolia*. Regarding poorly and moderately suitable classes, 10-17% of area will transition into adjacent classes. Additionally, 6-11% of historically highly suitable habitats will change to moderately or poorly suitable classes.

Spatial habitat loss and gain under future scenarios are shown in Fig. 5 [Figure 5: see original paper]. The potential distribution of *Picea crassifolia* is predicted to persist in the central and western study area, with slight decreases in the central region and increases mainly in the eastern region. This result likely reflects currently unsuitable regions becoming conducive to growth under future conditions, facilitating successful colonization by *Picea crassifolia*.

4.1 Model performance

Among the SDM techniques used, the MaxEnt algorithm demonstrated the highest precision for modeling *Picea crassifolia* distribution. MaxEnt is widely considered one of the most reliable SDM techniques and is increasingly used to model species distributions and explore environmental influences (Ehrlén and Morris 2015; Waldock et al. 2022; Elith et al. 2010).

Our results also demonstrate positive effects of data resolution on model performance, consistent with previous studies showing that refined predictor resolution increases predictive performance (Lembrechts et al. 2023; Chauvier et al. 2022). Higher spatial resolution enables more accurate description of study targets (Randin et al. 2009; Dobrowski 2011; Hannah et al. 2014; Lenoir et al. 2016;

Meineri and Hylander 2017). In contrast, environmental signals become fuzzier at coarser resolutions due to increased inaccuracies and uncertainties in species responses (Chauvier et al. 2022; Stoklosa et al. 2014), resulting in poorer model performance.

However, the limitations of AUC for evaluating model precision warrant attention. Although AUC is widely used to assess model accuracy (López-Ramírez et al. 2024; Kishore et al. 2024), this approach has drawbacks because omission and commission errors are equally weighted (Lobo et al. 2008; Wei et al. 2024). Future research should consider comprehensive analyses using multiple metrics such as the Kappa statistic, True Skills Statistic (TSS), and newer evaluation metrics (Somodi et al. 2024).

4.2 Variables contribution

Bio12 and aspect are indispensable variables for modeling *Picea crassifolia* distribution in the Qilian Mountain Nature Reserve, consistent with many existing studies (Tu et al. 2022; Zhao et al. 2010). Soil moisture is fundamental to ecosystems and key to vegetation establishment (Vereecken et al. 2022). Given the arid to semi-arid climate of the Qilian Mountain Nature Reserve (Gou and Zhu 2021), soil moisture may be primarily influenced by precipitation and secondarily modulated by topography (Sehler et al. 2019; Du et al. 2022).

The contribution of topographic variables increased with finer data resolution, highlighting the importance of high-resolution topographic data (Scales et al. 2016). Due to environmental heterogeneity and intraspecific interactions, *Picea crassifolia* exhibits patchy distribution within the study region (Kannagaraj et al. 2019; Du et al. 2021). Finer topographic predictors can sufficiently depict these patchy environmental characteristics, making local microclimate more influenced by local topography than by broad-scale climate factors (Lembrechts 2023). When using coarse data, climate-related factors are pivotal determinants of tree distribution (Oliveira et al. 2021), while topographic attributes such as elevation, slope, and aspect often demonstrate limited predictive capacity (Neilson 1995). At higher resolution, however, the influence of topographic variables is highlighted and more useful for modeling species habitat distribution.

4.3 Changes of the potential distribution to *Picea crassifolia*

Currently, potential habitats for *Picea crassifolia* are confirmed in the central and northern Qilian Mountains Nature Reserve, while the western region is unsuitable. These results align with the fact that *Picea crassifolia* is the main tree species in this area (Wang et al. 2019).

Results also showed that *Picea crassifolia* distribution will slightly increase under future scenarios, agreeing with previous studies (e.g., Xu et al. 2009). Specifically, *Picea crassifolia* is expected to gain habitat in the eastern part and lose habitat in the central part of the Qilian Mountains Nature Reserve. This change is attributable to regional climate variability driven by westerlies and monsoons (Li et al. 2016). Generally, *Picea crassifolia* performs well under Bio12 values of 330-430 mm and Bio10 values of 9-14°C (Peng et al. 2014). Significant temperature and precipitation fluctuations in the central area under future scenarios may exceed the temperature threshold suitable for *Picea crassifolia* (Xu et al. 2012).

4.4 Implications for *Picea crassifolia* management

Climatically suitable habitats for *Picea crassifolia* in the study region are expected to expand in the future, representing good news for forest management. *Picea crassifolia* could be planted in regions likely to become climatically suitable. Since our model predicted western habitat gains, we propose establishing priority plantations in this region.

Furthermore, we analyzed variation in *Picea crassifolia* habitats under different climate and topographic conditions, shown in Fig. 6 [Figure 6: see original paper]. Specifically, potential habitat gains were most notable at elevations of 2,350-2,700 m and 3,050-3,400 m a.s.l., slopes of 30°-45°, and northern (N) slopes. Habitat losses were concentrated at elevations of 2,000-2,350 m a.s.l., slopes of 45°-60°, and southern (S) slopes. Comparing gain and loss ratios across different geographic regions can identify suitable planting zones for the future. For elevation, habitats may decrease at lower elevations but increase at higher elevations, with maximum gains at 3,050-3,400 m a.s.l. under SSP585. The magnitude of suitable area reduction at 2,000-2,350 m a.s.l. increased with climate change intensity. For slope, habitat gains occurred mainly on slopes of 0°-45°, with maximum gains at 15°-30°, while changes on 45°-60° slopes were divergent. For aspect, *Picea crassifolia* would lose most potential habitat on southern slopes (S), with losses of 0.63%-1.2% under future scenarios. Potential habitat gains occurred on northern (N), north-western (NW), and north-eastern (NE) slopes, particularly N slopes, with maximum gains exceeding 1% under SSP585. These results indicate that areas characterized by high elevation, gentle slopes, and shady slopes are more suitable for *Picea crassifolia*, especially elevations of 3,050-3,400 m a.s.l., slopes of 15°-45°, and N slopes.

Habitat fragmentation indices for current and future conditions are shown in Fig. 7 [Figure 7: see original paper]. Indices were highest under SSP585 and lowest under current conditions. By 2080, ED and PD may increase by 3.19% and 4.20% on average, respectively, suggesting that climate change will expand *Picea crassifolia* habitats in a patchy manner. Therefore, natural fragmentation patterns should be considered (Littlefield et al. 2019). Still, these change

patterns can inform assisted species translocation efforts by identifying suitable target locations (Wang et al. 2018).

Overall, spatial and temporal area changes of *Picea crassifolia* can guide long-term range surveys to discover undiscovered critical habitats, thereby protecting the health and stability of endemic species and ecosystems in the region and assisting future management. Additionally, our research methods and qualitative conclusions may provide reference or guidance for other forest distribution studies in dryland mountains. However, further work on tree physiology, field investigations, and controlled experiments is required to understand and quantify impacts of individual factors and their interactions on *Picea crassifolia* forest distribution under changing climate.

5 Conclusions

This study used SDMs to examine the effect of topographic resolution on modeling *Picea crassifolia* distribution in the Qilian Mountains Nature Reserve. Results revealed that high-resolution topographic data increased prediction accuracy and affected variable importance. Aspect, enabling depiction of smaller *Picea crassifolia* patches, became the most important predictor at 30 m resolution, although Bio12 was most vital at 90 m resolution. *Picea crassifolia* distribution was located in the central and eastern Qilian Mountains Nature Reserve and is expected to increase under various future scenarios, particularly in the eastern region at elevations of 3,050–3,400 m a.s.l., slopes of 15°–45°, and north-facing slopes. Based on these results, we advocate for monitoring *Picea crassifolia* distribution at fine spatial resolution to identify targeted regions for planting, management, and sustainable development.

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Author Contribution

ZHANG Xiang: Investigation, Data curation, Formal analysis, Writing –original draft, Writing –review & editing.

GAO Linlin: Conceptualization, Methodology, Writing –review & editing, Funding acquisition.

LUO Yu: Investigation, Data curation.

MA Baolong: Investigation.

GOU Xiaohua: Conceptualization, Supervision.

DENG Yang: Conceptualization, Writing –review & editing, Supervision, Funding acquisition.

YUAN Yiyun: Data curation.

Ethics declarations

Availability of Data/Materials: The data underlying this article will be shared upon reasonable request to the corresponding author.

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Fig. 1 Location of the Qilian Mountains Nature Reserve.

Fig. 2 Area under the receiver operating characteristic curve (AUC) to assess representation of species distribution models (SDMs) with different modeling techniques and resolutions in simulating the spatial distribution of *Picea crassifolia* in the Qilian Mountains Nature Reserve. GLM: Generalized linear model; GAM: Generalized additive model; MARS: Multivariate adaptive regression spline; CTA: Classification tree; MaxEnt: Maximum entropy; AUC: The area under the receiver operating characteristic curve.

Fig. 3 Importance (%) of climate and topography variables in ensemble models at two resolutions. Bio10: Mean temperature of warmest quarter; Bio12: Annual precipitation.

Fig. 4 Current (1970–2000) potential distribution of *Picea crassifolia* in 90 m and 30 m MaxEnt models.

Fig. 5 Spatial loss and gain regions of distribution area for *Picea crassifolia* growth under future scenarios, obtained by kernel density analysis. (A) SSP126; (B) SSP245; (C) SSP370; (D) SSP585.

Fig. 6 Rate of gain and loss of *Picea crassifolia* habitats in different topography ranges under future scenarios, compared with current habitats.

Fig. 7 Disparity in habitat fragmentation indices across various scenarios.

Table 1 Statistics of habitat changes (km²) in four suitability classes for *Picea crassifolia* distribution under SSP126, SSP245, SSP370, and SSP585 scenarios. Change of suitable area: Divide future suitable area change by current suitable area (sum of poorly suitable, moderately suitable, and highly suitable area, ~5,110.65 km²).

Table 2 Transition of *Picea crassifolia* habitats (km²) in suitability classes across different periods. (Unit: km²)

Appendix 1 Correlation coefficients of 19 bioclimatic variables. $P < 0.001$, ; $P < 0.05$, ; $P < 0.01$, .

Appendix 2 Spatial loss and gain regions of distribution area for *Picea crassifolia* growth under future scenarios, obtained by kernel density analysis. (A) SSP126, (B) SSP245, (C) SSP370, (D) SSP585 for 2021-2040.

Appendix 3 Statistics of habitat changes in four suitability classes for *Picea crassifolia* distribution under SSP126, SSP245, SSP370, and SSP585 scenarios for 2021-2040. Change of suitable area: Current suitable area divides by future change area.

Appendix 4 Transition of *Picea crassifolia* habitats in suitability classes across different periods of 2021-2040. (Unit: km²)

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

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