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Original Article

Comparative Analysis of the Volume Growth of Oaks (*Quercus*) Across Regions of China

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Abstract:

Abstract: Oaks (*Quercus*) are a widely distributed and ecologically important genus in forests globally. However, their growth varies considerably across regions that vary in climate and soil conditions. Here, we systematically analyze the dynamics and regional differences in the volume growth of oaks, with the aim to provide scientific evidence useful for the sustainable management and ecological stewardship of oak forests. The results show that: (1) There are significant differences in the volume growth of oaks among regions of China. The southwestern region has the highest volume growth, with an average of 122.90 $m^3 \cdot hm^{-2}$, which is significantly higher than that of other regions, including the northeast (104.06 $m^3 \cdot hm^{-2}$), northwest (92.19 $m^3 \cdot hm^{-2}$), southeast (91.13 $m^3 \cdot hm^{-2}$), north central (53.47 $m^3 \cdot hm^{-2}$), and south central region (49.26 $m^3 \cdot hm^{-2}$). The observed differences are mainly attributed to the varying age group structures across regions, with a higher proportion of near-mature and mature forests in the southwestern, northeastern, and northwestern regions, while other regions have a larger proportion of young and middle-aged forests. (2) The volume growth of oak trees is significantly age dependent. In the early growth period (e.g., the first 100 years), they exhibit rapid growth, before entering a relatively stable growth phase. The southeastern region shows the highest growth, with the north central regions had slower growth. Notably, oaks in the northwestern region exhibit clear signs of early aging. (3) Climate and site conditions have a decisive impact on the growth of oak trees. The warm and humid climate of the south, along with diverse site conditions, provides a favorable environment for oak growth, whereas the cold and dry climatic conditions in the north somewhat limit their growth potential. Based on this, we recommend developing differential forest management strategies according to the climatic and site conditions of the regions, optimize stand structures, and promote the sustainable development of oak resources.

Keywords: Oak trees; Richards growth equation; Growth process; Forest management; Climate and site condition.

1. Introduction

Oaks (*Quercus spp.*) are among the most widely distributed groups of species in China (Du et al. 2021 and Wang et al. 2023). Because of their high adaptability and broad distribution (Chen et al. 2022 and Barsoum et al. 2015), oaks play a key role in timber production, carbon fixation (Vickers et al. 2023 and Guan et al. 2019), soil and water conservation, water source maintenance, and biodiversity preservation (Liao et al. 2021 and Fei et al. 2011). By quantifying the carbon storage capacity of oaks across geographic regions, we can evaluate regions important for formulating areas for timber production and carbon reduction strategies (Song et al. 2024). Moreover, the volume contained within oak forests is highly correlated with a number of ecological functions within forests. As a result, understanding the growth and production of oaks provides a baseline for assessing and enhancing the ecological services provided by oak forest ecosystems (Stefanska-Krzaczek et al. 2024).

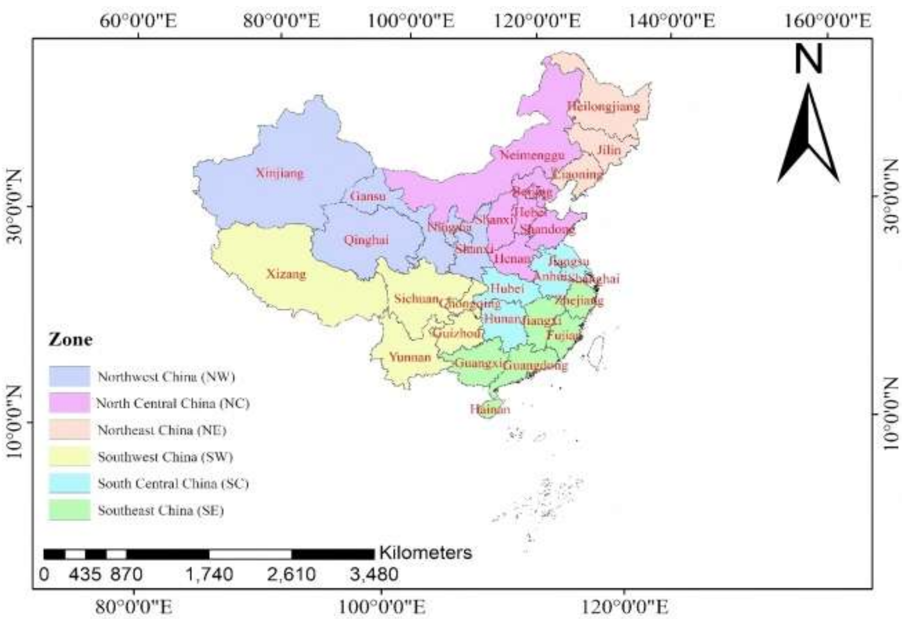
Oak forests differ in their growth characteristics geographically, implying that optimal harvesting cycles and utilization methods have regional variation. As a result, comparative analyses across these regional differences can provide important information for scientific management, including determining the maturation periods of oaks among regions, achieving sustainable utilization of timber resources, and formulating targeted forest management plans (Bou et al. 2019 and Stefanska-Krzaczek et al. 2024). Such comparative analyses also aid the exploration of mechanisms by which environmental factors influence the growth and development of oaks. Indeed, the management of natural oak forests has become a critical indicator of managing secondary forests in China, with its management quality directly affecting the overall level of forest resources (Chinese Society of Forestry, 2017).

Because oak growth differs greatly across regions, it is useful to conduct standardized cross-regional comparative analyses (Chen et al. 2022). However, to date, studies have used diverse research methodologies across studies and regions. These include growth models based on national forest resource survey data (Yan Wei et al. 2019), growth models using stand volume growth (Fu et al. 2017, Pienaar et al. 1984, and Matney et al. 1982) and systematic comparisons by constructing multi-species growth models (Ning et al. 2014). Given the broad distribution and significant growth differences of oaks across China, here we use a unified modeling approach to systematically analyze the regional differences in the volume growth of oaks. We argue that using such a unified modeling approach for comparative analyses of oak volume growth not only has important theoretical value, but also provides scientific evidence that can form the basis of regional forestry management.

2. Materials and Methods

2.1 Regional Volume Growth Models of Oak Trees

A recent study by Fu et al. (2022) used data from the fifth national forest resource inventory (1994-2018, conducted every five years) from across China, which covers plot and sample tree data across regions, tree species, and ages. They divide China's administrative divisions into six geographic regions based on provinces (Northwest, North Central, Northeast, Southwest, South Central, and Southeast (**Fig. 1**)).



They employed the Richards growth equation to fit the relationship between the hectare volume and age of the main dominant tree species across regions, with typically high model fits. This suggests a feasible pathway for large-scale comparisons of the volume growth of different tree species across regions. Here, we build on the results of Fu et al. (2022) and use the Richards growth equation to fit the relationship between the volume and age of oaks across the six regions of China. Specifically, the equation was:

$$V = a(1 - e^{-ct})^b \quad (1)$$

where V represents the hectare volume ($m^3 \cdot hm^{-2}$); t represents the stand age of the forest (a); a, b, and c are constants. The parameters a, b, and c in the volume growth equation are shown in **Table 1** (Fu et al. 2022).

Table 1 Parameters of oak tree growth derived from Richards growth equation among different regions of China

Region	Sample plots	Survey time	a	b	c	R^2
Northwest China (NW)	712	1994-2018	135.739	0.939	0.179	0.520
North Central China (NC)	1123	1994-2018	193.586	1.208	0.008	0.649
Northeast China (NE)	1067	1994-2018	171.960	2.029	0.032	0.776
Southwest China (SW)	828	1994-2018	267.122	1.185	0.011	0.712
South Central China (SC)	804	1994-2018	154.610	1.575	0.029	0.721
Southeast China (SE)	241	1994-2018	265.696	2.028	0.031	0.704

2.2 Oak Composition, Climate and Terrain Data in Different Regions of China

The main species of oaks from the different regions of China are shown in **Table 2** (State Forestry Administration of China. 2019). To examine the effects of climate and topography on the growth and distribution of oaks across China, we: (1) extracted climate data, including annual average temperature, annual average precipitation from the Resource and Environmental Science Data Platform (https://www.resdc.cn), (2) DEM (Digital Elevation Model), topographic data, including slope and aspect data from the National Earth System Science Data Center (https://www.geodata.cn).

Table 2 Tree species of oak trees in different regions of China

Region	Tree species
Northwest China	*Quercus mongolica*, *Quercus wutaishanica*, *Quercus variabilis*, *Quercus spinosa*
North Central China	*Quercus mongolica*, *Quercus wutaishanica*, *Quercus variabilis*, *Quercus acutissima*, *Quercus aliena*
Northeast China	*Quercus mongolica*, *Quercus wutaishanica*, *Quercus variabilis*, *Quercus acutissima*, *Quercus aliena*
Southwest China	*Quercus variabilis*, *Quercus acutissima*, *Quercus senescens*, *Quercus spinosa*, *Quercus semicarpifolia*
South Central China	*Quercus variabilis*, *Quercus acutissima*, *Quercus serrata*, *Quercus chenii*, *Cyclobalanopsis glauca*
Southeast China	*Quercus fabri*, *Quercus acutissima*, *Quercus variabilis*, *Quercus serrata*, *Lithocarpus glaber*

3. Results

3.1 Statistics of Oak Resources across Regions

We present results from the analysis of oak resources from across China in **Table 3**. Overall, the total area of oak forests cover 152,609 km², accounting for nearly 12% of the total forest resources available nationwide. Total wood volume of these trees was 13,865,677 m³, representing almost 10% of the national total forest volume. Across regions, oaks are mainly distributed in the Southwest, Northeast, and North Central regions. In contrast, the distribution of oaks is relatively scarce in the Northwest, Southeast, and Central South regions. Furthermore, the per-hectare volume in the Southwest, Northeast, and Northwest regions is relatively high, owing primarily due to a higher proportion of more mature forests, while it is lower in the Southeast, North Central, and Central South regions which have younger forests.

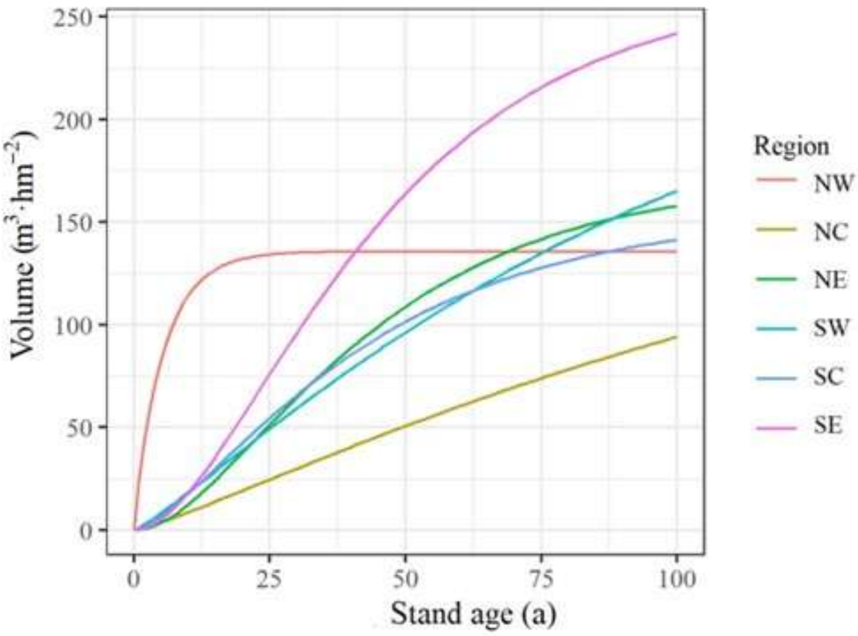
Table 3 Area and volume of oak trees in different regions of China

Region	Age group	Oak forests		
		Area （10^2·hm^2）	Volume （10^2·m^3）	Hectare volume （m3·hm^{-2}）
Northwest China	Young	3013	112708	37.41
	Middle-aged	3213	301439	93.82
	Near-mature	3045	349447	114.76
	Mature	2767	283400	102.42
	Over-mature	3688	402725	109.2
	Subtotal	15726	1449719	92.19
North Central China	Young	20092	612943	30.51
	Middle-aged	10052	621211	61.8
	Near-mature	5366	483010	90.01
	Mature	3716	355775	95.74
	Over-mature	540	51869	96.05
	Subtotal	39736	2124808	53.47
Northeast China	Young	10101	373569	36.98
	Middle-aged	7455	754472	101.2
	Near-mature	7676	1058780	137.93
	Mature	7873	1148751	145.91
	Over-mature	2605	380279	145.98
	Subtotal	35710	3715851	104.06
Southwest China	Young	16024	927617	57.89
	Middle-aged	8858	952375	107.52
	Near-mature	6147	942708	153.36
	Mature	7439	1391291	187.03
	Over-mature	3997	1006263	251.75
	Subtotal	42475	5220254	122.90
South Central China	Young	7420	250341	33.74
	Middle-aged	997	955384	95.67
	Near-mature	347	65336	188.29
	Mature	111	21601	194.6
	Over-mature	32	6113	191.03
	Subtotal	8907	438775	49.26
Southeast China	Young	5028	221194	43.99
	Middle-aged	3479	433565	124.62

	Near-mature	824	111553	135.38
	Mature	484	82833	171.14
	Over-mature	240	21104	87.93
	Subtotal	10055	916269	91.13
Total	Young	61678	2498372	40.51
	Middle-aged	34054	3158446	92.75
	Near-mature	23405	3010834	128.6
	Mature	22390	3283651	146.66
	Over-mature	11102	1868353	168.29
	Subtotal	152609	13865676	90.86

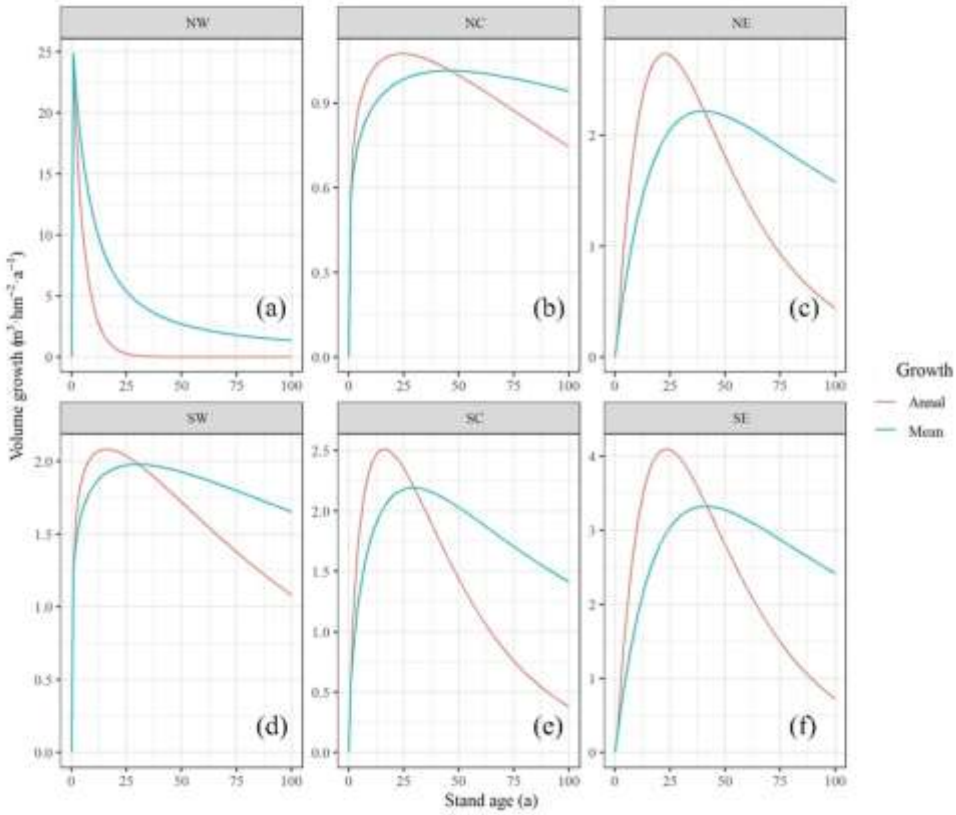
3.2 Volume Growth of Oaks across Regions

Using the Richards growth equation, we fitted the dynamic changes in the total volume growth of oak trees across regions over a period of 0 to 100 years (**Fig. 2**).



We find that the total volume growth of oaks was initially rapid due to early growth, which was followed by a gradual slowdown and levelling off as stand age increases. Notably, the total volume growth of oak trees in the southeast is substantially higher than in other regions, whereas the growth increment of oaks in the north central is the slowest. Furthermore, the total volume growth of oaks in the northwest is characterized by a rapid growth increment during the first 0 to 25 years, followed by a marked stagnation in total volume growth after 25 years.

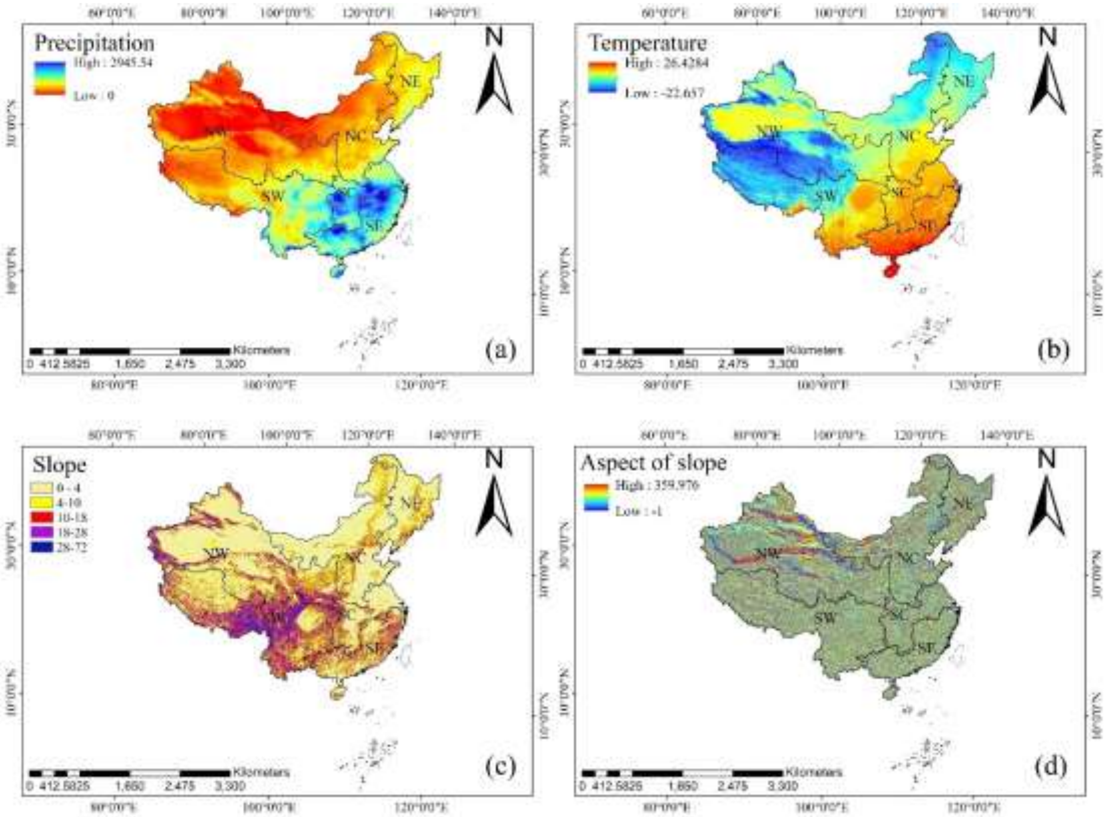
The average volume growth increment and annual volume growth increment of oaks across regions is presented in **Fig. 3**.



In the northwest, the average volume growth increment and annual growth increment peak in the first year, after which, the average volume growth increment exceeds the annual growth increment (i.e., the first year is considered the age of maturity for oaks in the northwest). In the north central, the annual growth increment exceeds the average growth increment from 0 to 47 years, after which they become similar, and then the average volume growth increment increases again (i.e., the 47th year is estimated as the age of maturity). In the northeast, the annual growth increment also remains higher than the average growth increment from 0 to 41 years, after which both growth increments equalize and the average volume growth increment exceeds the annual growth increment (i.e., the 41st year is the age of maturity). In the southwest, the annual growth increment exceeds the average growth increment from 0 to 31 years, peaking at 31 years, after which the average volume growth increment surpasses the annual growth increment (i.e., the 31st year is the age of maturity). In the central-south region, the annual growth increment is higher than the average growth increment from 0 to 30 years, after which the average volume growth increment exceeds the annual growth increment (i.e., the 30th year is the age of maturity). Finally, in the southeast region, the annual growth increment remains above the average growth increment from 0 to 42 years, after which the average volume growth increment exceeds the annual growth increment (i.e., the 42nd year is the age of maturity).

3.3 Analysis of Climate and Topographical Variation Characteristics across Regions

The distribution of climate and topography across regions is illustrated in **Fig. 4**, particularly showing significant variation between the north and south. Overall, the annual precipitation and average annual temperature are higher in the southern regions compared to the northern regions. Topographically, the southwestern region has the most substantial elevational variation, with some areas reaching altitudes of up to 4000 meters.



Climate and growth characteristics of the different regions are presented in **Table 4**. The southeastern region benefits from a maritime climate, with consistently high temperatures and abundant rainfall, resulting in good growth conditions for oaks, particularly *Q. fabri*, and *Q. acutissima*. However, frequent natural disasters (e.g., typhoons) negatively impact on oak growth. The central-southern and southwestern regions have warm and humid climates, which facilitates rapid growth in oaks. In the high-altitude areas of the southwest, *Q. semicarpifolia*, which adapt well to cooler and windy climates thrive.

Table 4 Climatic conditions and growth characteristics of oak trees in different regions of China

Region	Climatic Conditions and Growth Characteristics
Northwest	The climate is arid, with relatively barren soil. Oaks grow relatively slowly in this region and tend to be smaller in stature. Their demand for moisture is difficult to meet in such a dry environment, resulting in certain limitations on their growth. However, some drought-adapted species, such as *Q. mongolica*, can survive in harsher conditions.
North Central	The climate is relatively arid, with limited precipitation and higher temperatures in summer. The growth of oaks is generally moderate, but it may be limited compared to areas with more abundant rainfall. Growth of *Q. mongolica* is greatly influenced by water availability.
Northeast	The winter is cold and long, while the summer is warm and humid, with relatively abundant rainfall. Oak grow relatively quickly, producing high-quality timber with sturdy trunks. Due to the low winter temperatures, oaks have a certain degree of cold resistance, such as *Q. wutaishanica*.
Southwest	The terrain is complex, and the climate is diverse, featuring high mountains and canyons with significant elevation differences. In high-altitude areas, the climate is cold and precipitation is abundant; whereas in low-altitude areas, it is relatively warm and humid.

	The growth of oaks is highly variable.
South Central	The climate is warm and humid, with abundant precipitation and distinct seasons. These climatic conditions are suitable for the growth of oaks that grow relatively quickly, with tall plants and lush branches and leaves. The oaks in this region can fully utilize the favorable water and heat to perform well.
Southeast	Near the ocean, the climate is significantly influenced by the sea, with high temperatures and heavy rainfall in summer, and mild and less rainy conditions in winter. Oaks grow relatively quickly; however, due to the frequent occurrence of natural disasters such as typhoons, their growth can be reduced and/or mortality increased.

Conversely, the northwestern and north central regions have more arid climates, nutrient poor soils, and highly seasonal temperature differences. These environments support more drought-resistant oak species such as *Q. mongolica* and *Q. wutaishanica*, which grow more slowly and tend to be relatively slender. Although the northeast region has long and cold winters, it experiences warm and humid summers with relatively rich precipitation, allowing species like *Q. mongolica* and *Q. wutaishanica* to grow well, producing quality timber with sturdy trunks.

Table 5 Growth differences and management suggestions of Oaks in different regions

Site and Management		Southern China	Northern China
Climate	Temperature	The relatively high temperature may extend the growth cycle of some oak species adapted to warmer climates, and they may also maintain a certain amount of growth during the winter.	In winter, the cold climate allows varieties such as *Q. mongolica* to possess strong cold resistance, enabling them to adapt to lower temperatures and survive the winter.
	Precipitation	With abundant rainfall, the root system of oaks may be relatively shallow, and it is important to consider drainage to prevent waterlogging.	Precipitation is relatively scarce, and the growth of oak trees needs to adapt to a relatively arid environment, with their root systems often growing deeper to absorb water from deeper layers.
Soil	Soil texture	Soil types are diverse but relatively acidic. Oaks can adapt to these acidic soils and effectively absorb elements like iron and aluminum.	The soil has a relatively heavy texture. Oaks adapt to this soil environment for growth.
	Soil fertility	Although the soil has relatively high fertility, nutrients are lost quickly due to erosion. It is important to pay attention to timely nutrient supplementation, especially during the vigorous growth period.	The formation and release rate of soil fertility is relatively slow, and the growth increment of oak trees may be relatively slow as well, requiring measures such as reasonable fertilization to supplement nutrients.

Growth	Growth increment	Grows relatively quickly in a suitable warm and humid environment.	The growth increment is relatively slow in cold and arid environments.
	Morphological characteristics	The growing season is long, the trees are tall and upright, the branch angles are relatively large, and the foliage is more abundant.	Due to factors such as a shorter growing season and lower light angles, trees may be relatively short and stout with smaller branching angles to adapt to cold climates and snowy environments.
Management	Selection of planting varieties	Select oak species that can adapt to warm, humid climates and acidic soils. At the same time, it is important to choose varieties with resistance to pests and diseases.	Choose cold-resistant varieties that can better adapt to the low-temperatures of the north, thus reducing the risk of frost damage. When selecting seedlings, choose those with well-developed root systems and strong resistance to improve their survival rate in the harsh environments.
	Soil management	Due to the high soil acidity, alkaline substances such as lime can be added to adjust the soil pH to meet the requirements of certain oaks. At the same time, a good drainage system can prevent water levels that could lead to root rot.	Heavy clay soils can be improved by adding organic materials such as leaf mold and manure, which enhances soil aeration and water retention. During the dry season, irrigate timely, using water-saving methods such as drip irrigation or subsurface irrigation.
	Pest and disease control	Oaks are susceptible to various pests and diseases, such as aphids and scale insects. It is important to enhance monitoring and employ biological control methods, while also using pesticides judiciously to avoid environmental pollution.	Focus on preventing and controlling diseases and pests that are prone to thrive in cold and dry environments. During the prevention and control process, a combination of physical and chemical methods can be employed, such as clearing away dead branches and fallen leaves to reduce breeding sites for pathogens, and promptly spraying fungicides at the initial onset of disease.
	Tending and management	When pruning, maintain ventilation and light	Before winter, appropriate pruning can be carried out

		penetration in the tree crown to promote healthy growth of the trees. For densely growing stands, thinning can be help improve light and ventilation conditions within the forest. At the same time, appropriate fertilization can be applied to promote the rapid growth of oak trees.	to remove diseased and weak branches, reducing nutrient consumption. This also facilitates the shaping of the tree and enhances its resistance to wind and snow. During the growing season, remove weeds to prevent competition for nutrients between the weeds and the oak trees.

4. Discussion

Despite the widespread distribution of oaks across China, they vary substantially in their rates of growth across regions. Climate and local site conditions play a predominant role in driving these differences (Fang et al. 2012, and Gao et al. 2017). The southeast region features a warm and humid climate, which facilitates the fastest growth of oak trees in this area; in contrast, the north central region has an arid climate with substantial seasonal variation in temperature, resulting in the slowest growth increment. In the northeast, central south, and southwest regions, the summer climate is warm with relatively high rainfall, suitable, resulting in moderate growth increments. The northwest region is more arid, with nutrient-poor soils, leading to fast early growth, but slower growth later (see **Table 4**).

Overall growth conditions for oaks tend to be better in the south compared to the north, primarily in accordance with variation in favorable climate conditions (Zadworny et al. 2014 and Perez-Giron et al. 2022). The climate in the southern region is warm with abundant rainfall, and the soil types are fertile and rich in organic matter. Furthermore, the complex terrain creates unique microclimates and rich biodiversity, providing a favorable environment for oak growth. Therefore, the southern region primarily features species with faster growth increments, longer growing seasons, and tall, robust forms with dense foliage. In contrast, the northern climate is generally cold and dry with heavy clay soils, restricting oak growth. As a result, species such as *Q. mongolica* and *Q. wutaishanica* primarily thrive in the north (Li et al. 2024 and Chen et al. 2018), with slower growth increments, short growing seasons, and stout tree forms adapted to cold climates and snow cover (see **Table 2**).

Based on the substantial differences in the growth conditions of oaks between southern and northern China, appropriate management measures should be chosen in different regions (Molder et al. 2019 and Albert et al. 2017). Specific management recommendations include: (1) Species selection: In southern regions, oak species that are adapted to warm, humid climates and acidic soils, with strong disease and pest resistance, should be chosen. In northern regions, oak species suitable for cold, arid climates that exhibit strong resilience should be selected. (2) Soil management: Southern regions typically have acidic soils, and lime or other alkaline materials can be added to adjust soil pH to meet the requirements of certain oak varieties. In northern regions, heavy clay soils can be improved by adding organic materials (such as leaf mold and manure), and water-saving irrigation methods, such as drip irrigation or seepage irrigation, should be used to enhance water utilization efficiency (Long. 2021). (3) Pest and disease control: In southern regions, biological control methods targeting common pests, such as aphids and scale insects, should be employed, including the release of natural enemies, while using chemical agents judiciously to avoid environmental pollution. In northern regions, an integrated approach combining physical and chemical methods should be emphasized to control diseases that easily proliferate in cold, dry environments. (4) Maintenance management: In southern regions, regular pruning should be conducted to maintain ventilation and light penetration in the canopy. For dense stands, thinning can be performed to improve light and ventilation within the forest (Du et al. 1996 and You et al. 2015). In northern regions, timely pruning should take place before winter to reduce nutrient consumption, which aids in shaping the tree and enhancing its resistance to wind and snow (Chen et al. 2021).

5. Conclusions

Here, we employ a unified modeling approach to systematically analyze the regional differences in the volume growth oaks. The substantial differences we observed among in climate and site conditions are key factors leading to the growth disparities of oaks, particularly between northern and southern China. In southern China, particularly in the southwest, the warm and humid climate is favorable for oak growth. Similarly, the climatic conditions in central and southeastern coastal areas also benefit oak growth. In contrast, the overall growth is generally low in the north, coinciding with severe local climate and site conditions. Notably, oaks in the northwest region exhibit characteristics of early senescence, while those in north central grow slowly. As one of the most important groups of trees in the country, oaks have significant economic, ecological, and social value. Therefore, future management strategies for oaks should be tailored to the specific climate and site conditions, optimizing forest structure and promoting sustainable forestry development.

Data availability

Data are available on request.

Competing interests

The authors declare that they have no conflict of interest.

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Authors' contributions

Yuwen Luo analyzed the data and wrote the manuscript,
Zongzheng Chai wrote and reviewed the manuscri pt.

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