

Article

Spatiotemporal Characteristics of Oxygen Content in the Vegetation Growing Season of Qinghai Province Based on Vertical Gradients

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Abstract

To reveal the spatiotemporal variations in near-surface oxygen content during the growing season across different altitudinal gradients in Qinghai Province and to deepen the understanding of oxygen cycling in plateau ecosystems, this study analyzed daily observations from 12 monitoring stations spanning three elevation ranges (1500–2500 m, 2500–3500 m, and 3500–4500 m) during the 2022–2023 growing seasons (March–July). The Mann–Kendall test was employed to detect temporal trends, variability indices such as standard deviation and coefficient of variation were used to quantify fluctuation intensity, Kernel density estimation (KDE) was applied to characterize distributional features, and the Kruskal–Wallis test was conducted to assess statistical significance. The results indicate that: (1) oxygen content showed a significant increasing trend at all three altitudinal gradients, with the strongest rise at low elevations and the weakest at high elevations; (2) fluctuation intensity exhibited clear spatial heterogeneity, with the most pronounced variability in summer at low elevations, a distinct peak in June at mid-elevations, and overall stability at high elevations; and (3) KDE analysis revealed a broader distribution and higher frequency of extreme oxygen values at low elevations, while mid- and high-elevations displayed more concentrated distributions. Both the Kruskal–Wallis test and post hoc comparisons confirmed highly significant differences among the three elevation ranges. These findings demonstrate that elevation is a key factor influencing the spatiotemporal distribution of near-surface oxygen content during the growing season in Qinghai Province. Differences are not only evident in absolute oxygen levels but also in fluctuation intensity and distributional characteristics. This study provides empirical evidence for understanding oxygen variability mechanisms on the plateau and offers theoretical and practical references for ecological management and health risk prevention in high-altitude regions.

Keywords: altitude gradient; near surface atmospheric oxygen content; Qinghai Province; Kernel density estimation; significant difference test; fluctuation intensity



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1. Introduction

Oxygen (O₂) is the second most abundant gaseous component in the atmosphere after nitrogen and constitutes an indispensable substance for sustaining life processes and maintaining ecosystem functioning [1]. For a long time, the classical understanding has been that

with increasing altitude, what changes significantly are air pressure and oxygen partial pressure, while the volumetric fraction of oxygen in the air (approximately 20.946%) remains nearly constant across elevations [2,3]. However, recent large-scale field measurements on the Qinghai–Tibet Plateau (QTP) have challenged this consensus, showing that near-surface oxygen content exhibits significant spatial and seasonal differences (with summer averages about 0.31% higher than winter), influenced not only by elevation but also jointly by air temperature and vegetation conditions [4–6]. These findings provide observational evidence to revise the long-standing assumption of “constant oxygen content.” High-altitude regions (typically ≥ 2500 m) are characterized by low-oxygen environments, which lead to a series of cardiovascular, respiratory, and metabolic health risks [7–11]. In Qinghai and Tibet, where medical conditions and environmental factors intersect, life expectancy has long remained below the national average, highlighting the practical significance of near-surface oxygen variation for public health [12].

The Qinghai–Tibet Plateau, the world’s highest and most topographically complex plateau region, serves not only as an important ecological security barrier for China and even Asia, but also as one of the areas most strongly affected by global climate change [13–19]. A growing body of research has revealed that oxygen content in the Qinghai–Tibet Plateau region is jointly driven by multiple natural factors, including elevation, air temperature, vegetation conditions, and atmospheric pressure, showing marked regional and seasonal fluctuations [5,20,21]. Particularly within Qinghai Province, where geographic units differ greatly in topography, climate, and ecosystem structure [22], oxygen content may exhibit heterogeneous variation patterns; however, relevant comparative studies remain insufficient. Previous studies, employing methods such as electrochemical measurements, remote sensing vegetation index analysis, and regression modeling, have systematically explored the spatiotemporal variation of oxygen content and its dominant controlling factors [20,21]. For example, based on field data from 2018 to 2020, one study found a strong negative correlation between oxygen content and elevation ($R^2 = 0.7367$), as well as positive correlations with temperature and vegetation cover; together, these three variables explained approximately 82% of the variation in oxygen content [20]. Another study reported that, at the same site, average oxygen content in summer was about 0.31% higher than in winter, reflecting the significant influence of temperature on oxygen dissolution and gas exchange processes [21]. Furthermore, with the intensification of climate warming, some studies have suggested that oxygen variation may also be associated with coupled mechanisms involving temperature, vegetation, and photosynthesis, potentially affecting health risks for plateau residents [6].

Qinghai Province, located in the northeastern part of the Qinghai–Tibet Plateau, is an integral component of the plateau and is characterized by diverse landforms and pronounced regional differences [23]. The period from March to July corresponds to the primary vegetation growing season in Qinghai. With rising temperatures, snowmelt, and enhanced evapotranspiration, ecosystem photosynthesis becomes increasingly active, strengthening regional oxygen production capacity and leading to temporal fluctuations in near-surface oxygen [24,25]. Meanwhile, due to differences in elevation, landforms, soil moisture, and vegetation types, oxygen variation patterns under the same climatic background show significant spatial heterogeneity. Although existing research has examined the spatiotemporal variation of oxygen content and its controlling factors in the Qinghai–Tibet Plateau, studies at the provincial scale—especially concerning different elevation gradients during the vegetation growing season in Qinghai—remain scarce. On the one hand, most previous studies focused on the whole plateau or on multi-zone field sampling sites, indicating significant spatial heterogeneity in Qinghai, yet systematic comparative studies across elevation gradients are still lacking. On the other hand, March–July coincides

with the most active season of vegetation growth on the plateau and the peak period of ecosystem carbon sequestration and oxygen release [26]. Importantly, the spatiotemporal fluctuation of near-surface oxygen not only reflects atmospheric environmental changes but also directly influences ecosystem processes and human health [27–29]. Oxygen levels determine photosynthetic and carbon cycle efficiency [30], while also critically affecting respiratory and cardiovascular adaptation in high-altitude residents and tourists. Therefore, an in-depth investigation into the fluctuation trends and spatiotemporal characteristics of oxygen content during this period is of great theoretical and practical significance for understanding the natural drivers of atmospheric oxygen cycling in plateau regions, elucidating the response pathways of ecosystems to climate change, and guiding health protection and tourism management in high-altitude areas.

This study focuses on different altitudinal gradients in Qinghai Province and is based on near-surface oxygen content data collected in 2022 and 2023 using zirconia and electrochemical oxygen sensors at meteorological stations. Methodologically, the Mann–Kendall trend test was employed because it does not require distributional assumptions and is robust to outliers, making it well suited for long-term trend detection in non-normal environmental datasets. Variability indices were applied to capture multi-dimensional differences in oxygen stability, while Kernel density estimation (KDE) was used to reveal distributional characteristics and the occurrence probability of extreme values. The integrated application of these methods enables a comprehensive characterization of the spatiotemporal features of oxygen content and an analysis of its evolutionary patterns during the growing season in Qinghai Province. Specifically, we aimed to answer three questions: (1) What are the temporal variation trends of oxygen content across different elevation gradients during the vegetation growing season? (2) How does the fluctuation intensity (stability) of oxygen content differ across elevations and seasons? (3) Are there significant differences in oxygen content distribution patterns among different elevation gradients? Beyond methodological contributions in multi-angle data interpretation, this research holds academic and practical significance. The findings enhance the understanding of oxygen cycling on the plateau and provide valuable data support and theoretical reference for climate–ecological research on the Qinghai–Tibet Plateau as well as for health risk early warning in high-altitude regions.

2. Data Analysis

2.1. Study Area Overview

Qinghai Province is located in the northwest of China and is one of the main regions of the Qinghai–Tibet Plateau [31]. The terrain is high and the landforms are complex, with an average elevation of over 3000 m. Climatically, Qinghai Province belongs to a plateau continental climate, characterized by large annual temperature differences, strong solar radiation, and uneven spatiotemporal distribution of precipitation [32]. Due to the combined influence of high altitude, rarefied atmosphere, and intense solar radiation, the atmospheric oxygen content in this region remains consistently low, distinctly different from that of low- and mid-altitude areas. Previous studies have found that near-surface atmospheric oxygen content in Qinghai generally shows a spatial pattern of being higher in the south and lower in the north, and lower in the east than in the west [33]. Reduced atmospheric pressure leads to a decrease in the number of oxygen molecules per unit volume of air, while lower temperatures and reduced air density further diminish the efficiency of human oxygen uptake. Consequently, a unique plateau hypoxic environment is formed. Based on the specific topographic and geomorphological features of Qinghai Province, this study classified oxygen monitoring sites into three altitudinal gradients: low

elevation (1500–2500 m), mid-elevation (2500–3500 m), and high elevation (3500–4500 m). The natural geography of Qinghai Province is shown in Figure 1.

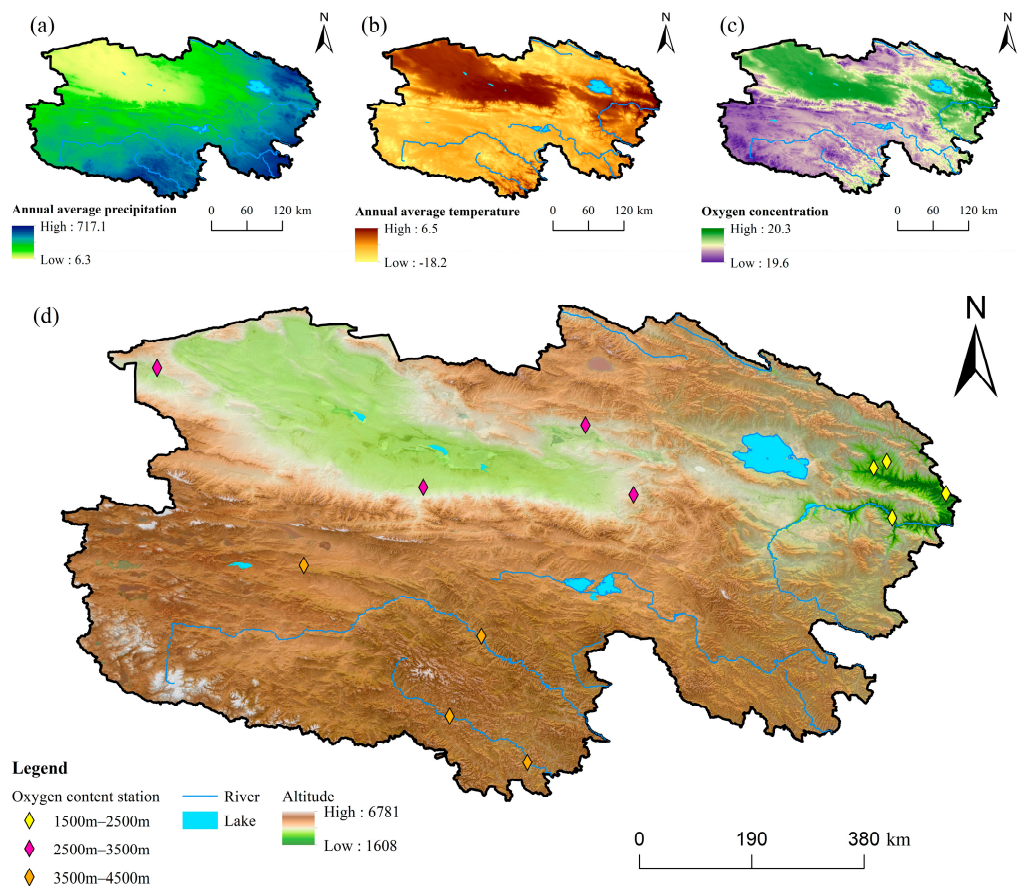


Figure 1. Regional overview of Qinghai Province: (a) Annual precipitation (b) Annual temperature (c) Near-surface oxygen concentration (d) Topography and oxygen station locations.

2.2. Data Sources

- (1) Oxygen content data were obtained from real-time monitoring at meteorological stations, using both zirconia-based and electrochemical oxygen sensors. The instrument used by the meteorological station to measure oxygen concentration is the TD600S-O₂-A oxygen content analyzer produced in China, installed at a height of 2 m above the ground, with oxygen concentration measured in%.
- (2) Spatial distribution data of oxygen content were derived from the Near-Surface Oxygen Content Dataset of the Qinghai–Tibet Plateau (2017–2022) provided by the National Tibetan Plateau Data Center [33].
- (3) Historical temperature data were obtained from the 1 km Monthly Mean Temperature Dataset for China (1901–2024), also from the National Tibetan Plateau Data Center [34].
- (4) Historical precipitation data were obtained from the 1 km Monthly Precipitation Dataset for China (1960–2020), sourced from the China Scientific Data journal (Chinese and English online editions) [35].

2.3. Research Methods and Ideas

The Mann–Kendall (M–K) trend test is a nonparametric statistical method widely applied for detecting long-term monotonic trends in time series, particularly in meteorology, hydrology, and environmental sciences for datasets that do not follow a normal distribution [36–38]. Due to its robustness against outliers and lack of assumptions regarding

linearity, it is particularly suitable for identifying trends in daily oxygen content time series in this study.

The method constructs a statistic S to measure the sequential differences among elements in the sample series, defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (1)$$

where x_i and x_j represent the i th and j th observations in the time series, respectively, and $\text{sgn}(\cdot)$ is the sign function, returning -1 , 0 , or 1 to indicate the direction of difference.

If no tied values exist, the variance of S is calculated as:

$$\sigma_S^2 = \frac{n(n-1)(2n+5)}{18} \quad (2)$$

When ties occur, the variance is adjusted to:

$$\sigma_S^2 = \frac{n(n-1)(2n+5) - \sum t_p(t_p-1)(2t_p+5)}{18} \quad (3)$$

where t_p denotes the number of ties for the p th value. The standardized normal statistic Z is then computed as:

$$Z = \begin{cases} \frac{S-1}{\sigma_S}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sigma_S}, & \text{if } S < 0 \end{cases} \quad (4)$$

Trend significance is determined by comparing Z with the critical value $Z_{1-\alpha/2}$. In this study, a 99% confidence level was adopted, and $|Z| \geq 2.58$ indicates a statistically significant trend. The M–K test was implemented in MATLAB R2022b for oxygen content time series across different altitudinal gradients in Qinghai Province, calculating S , Z , and their significance levels, and visualizing results as bar charts to illustrate trend characteristics at each gradient. It should be noted that the M–K trend tests in this study were conducted separately across three elevation gradients, which theoretically raises the possibility of inflated Type I error rates due to multiple comparisons. However, since the samples at different gradients are independent and the significance levels of the test results are extremely high (all passing the $\alpha = 0.01$ threshold), the conclusions remain robust even under a stringent Bonferroni correction (adjusted threshold $\alpha = 0.01/3 \approx 0.0033$). Therefore, no additional correction methods were introduced in this study.

In examining the spatiotemporal differences of oxygen content during the vegetation growing season across altitudinal gradients, quantifying fluctuation intensity is as important as analyzing mean levels and trends. Fluctuation intensity reflects temporal stability in oxygen content and indirectly indicates the extent to which environmental variability perturbs oxygen concentration. Regions with larger fluctuations are likely more sensitive to short-term climatic variability or extreme weather events, while regions with smaller fluctuations may exhibit more stable ecological conditions throughout the growing season.

This study employed four statistical measures to quantify fluctuation intensity: standard deviation (SD), coefficient of variation (CV), range, and interquartile range (IQR). These metrics capture both absolute and relative variability and offer complementary advantages for comparing different elevations and time periods.

Standard deviation (SD) measures the absolute magnitude of variation from the mean, with higher values indicating greater oxygen content variability during the period [39–41]. Coefficient of variation (CV), defined as the ratio of SD to the mean (expressed as a per-

centage), removes the influence of mean magnitude and is thus more suitable for relative comparisons between different elevation gradients [42–44].

$$SD = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2}, \frac{SD}{\bar{x}} \quad (5)$$

where x_i is the observation, $\bar{x}$ is the sample mean, and n is the sample size.

Range is the difference between the maximum and minimum values, offering a direct indication of variability but being sensitive to outliers:

$$\text{Range} = \max(x_i) - \min(x_i) \quad (6)$$

Interquartile range (IQR), the difference between the 75th and 25th percentiles, provides a robust measure of typical variability by excluding the influence of extreme values [45]:

$$\text{IQR} = Q75 - Q25 \quad (7)$$

In the computation, station data were grouped by elevation (1500–2500 m, 2500–3500 m, and 3500–4500 m), with missing values removed. Monthly values of the four indicators were calculated to reveal fluctuation characteristics within the growing season and differences among altitudinal gradients. Heatmaps were used to visualize the two-dimensional distribution of these metrics across “month–elevation” space, highlighting the coupled temporal–spatial patterns of fluctuation intensity. Heatmaps, through the use of color gradients, can rapidly reveal seasonal peaks at the monthly scale as well as spatial patterns across different elevations, thereby facilitating the identification of interactive characteristics of fluctuation intensity in both temporal and spatial dimensions. This analysis provides a quantitative basis for understanding seasonal oxygen variability and supports subsequent significance testing and trend analysis.

To characterize the probability distribution of oxygen content across different elevation gradients during the growing season, KDE was applied for distribution fitting and visualization. KDE is a nonparametric method that estimates the overall probability density by superimposing smoothed kernel functions at each observation point. Compared with histograms, KDE offers smoother, continuous curves and does not rely on prior distributional assumptions, making it suitable for exploring distributional features of environmental variables [46–48]. In the calculation process, the oxygen content data at different elevation gradients were subjected to density estimation using a Gaussian kernel. As the most commonly used kernel function in KDE, the Gaussian kernel provides good smoothness and is particularly suitable for continuous environmental data [49].

The general form of the KDE is:

$$\hat{f}(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right) \quad (8)$$

where $\hat{f}(x)$ is the estimated density at point x ; n is the sample size; $K(\cdot)$ is the kernel function, here taken as a Gaussian kernel; and h is the bandwidth controlling the smoothness of the estimate. Bandwidth selection critically affects results; in this study, MATLAB’s default “Silverman’s rule” was adopted to balance smoothness and detail preservation. Based on the sample size in this study, the estimated bandwidth was approximately $h \approx 0.024\text{--}0.035$ (with slight variations across different elevation gradients). This range provides smoothed yet detailed density curves under the typical fluctuation amplitude of oxygen concentration distributions, and is therefore well suited to the present dataset.

KDE curves for the three elevation gradients were plotted in the same coordinate system, with the area under each curve normalized to 1 for direct probability density comparison. Differences in peak positions, curve shapes, and distribution widths were examined to identify concentration ranges, skewness characteristics, and variability for each gradient, providing a probabilistic perspective for interpreting spatiotemporal differences.

To assess the statistical significance of oxygen content differences among altitudinal gradients during the growing season, the Kruskal–Wallis (KW) H test was applied for nonparametric multiple-group comparison, followed by post hoc pairwise comparisons when overall differences were significant. The KW test offers a robust nonparametric approach for detecting overall differences, while post hoc analysis pinpoints the specific sources of variation, thereby enhancing interpretability and scientific rigor [50,51].

The KW test, based on rank-sum comparisons, is suitable for independent samples that do not meet the assumptions of normality or homogeneity of variance. The test involves pooling all samples, ranking them, and comparing rank sums among groups to determine whether their distributions differ significantly. In this study, the three elevation gradients (1500–2500 m, 2500–3500 m, and 3500–4500 m) were treated as independent groups, with daily oxygen content data input for testing. The test statistic is given by:

$$H = \frac{12}{N(N+1)} \sum_{j=1}^k \frac{R_j^2}{n_j} - 3(N+1) \quad (9)$$

where k is the number of groups, n_j is the sample size of the j th group, R_j is the sum of ranks for the j th group, and N is the total sample size. A result of $p < 0.05$ indicates that at least two groups differ significantly.

When the KW test yielded significant results, Dunn's test with the Bonferroni adjustment was further applied for pairwise comparisons, as the Bonferroni method is more conservative and can provide more robust conclusions when the sample size is limited. This method performs pairwise rank mean comparisons while adjusting p -values to control Type I error inflation from multiple testing. Results were tabulated, including group comparisons, rank mean differences, confidence intervals, and adjusted p -values, and significance columns were added in the figures to intuitively display the differences. This approach not only determines whether overall differences exist but also specifies which elevation gradients differ significantly.

In the difference tests, the daily observation sequences at different elevation gradients were treated as independent sample groups. It should be noted that no additional treatment was applied to account for potential temporal autocorrelation within the daily sequences or spatial autocorrelation among the stations, which may to some extent affect the independence assumption of the statistical tests. Therefore, the related results should be interpreted primarily as comparisons of trends and distributional characteristics rather than as strict inferences under fully independent samples. This limitation will be addressed in future studies by introducing block averaging or time-series modeling approaches.

3. Results

3.1. Distribution and Trend of Oxygen Content at Different Altitude Gradients

In this section, descriptive statistics and the Mann–Kendall trend test were employed to characterize the daily oxygen content time series during the vegetation growing season (March–July) across different elevation gradients, with a focus on mean levels, variation trends, and stage-specific differences in order to reveal the dynamic differentiation patterns along elevation. Daily oxygen content time series for the three elevation ranges—1500–2500 m, 2500–3500 m, and 3500–4500 m—were visualized and analyzed, and Figure 2

presents the daily oxygen content series and the corresponding linear trend lines for the three elevation gradients (1500–2500 m, 2500–3500 m, 3500–4500 m). Through this figure, the trajectories and differences in growth amplitudes across elevations can be visually compared. Overall, all gradients exhibited an increasing trend in oxygen content during the growing season, but differences were evident in the rate of increase, fluctuation amplitude, and stage-specific features.



Figure 2. Oxygen content changes during growing season at altitudes: (a) 1500–2500 m (b) 2500–3500 m (c) 3500–4500 m.

At the low-elevation gradient (1500–2500 m), the overall mean oxygen content was 20.80, with a maximum of 20.95 and a minimum of 20.58. A continuous upward trend was observed throughout the growing season. The mean value was about 20.55 on March 1, rising to around 20.95 by July 10, with a total increase of approximately 0.40. The curve exhibited a generally steady trajectory with certain inter-daily fluctuations, particularly during May to June, when the increase was more pronounced. The slope of the trend line was the steepest among the three gradients, indicating the fastest rate of oxygen increase within the study period.

At the mid-elevation gradient (2500–3500 m), oxygen levels were lower than those at low elevations, with a mean of 20.61, a maximum of 20.88, and a minimum of 20.52. The mean value was 20.52 on March 1, rising to about 20.70 by July 15, with a total increase of roughly 0.22, which was smaller than that at low elevations. The curve showed temporary peaks on April 12 and June 27, but declined rapidly after each peak. Overall fluctuations were slightly larger than those at high elevations. The slope of the trend line was intermediate, suggesting a modest upward trend but at a slower rate compared with low elevations.

At the high-elevation gradient (3500–4500 m), oxygen content was the lowest, with an overall mean of 20.73, a maximum of 20.90, and a minimum of 20.62. The mean value was 20.62 on March 1, rising to about 20.83 by July 15, with a total increase of 0.21. The overall changes were relatively steady, but a noticeable increase occurred on July 9, peaking at around 20.90. Inter-daily fluctuations were relatively small, and the curve was smoother compared with other gradients. The slope of the trend line was smaller than that at low elevations, indicating a steady upward tendency overall.

To quantitatively assess the significance of these trends, the Mann–Kendall (M–K) trend test was applied to the three datasets (Figure 3). The M–K test's advantage lies in its independence from distributional assumptions, making it suitable for non-normal and outlier-prone environmental monitoring data.

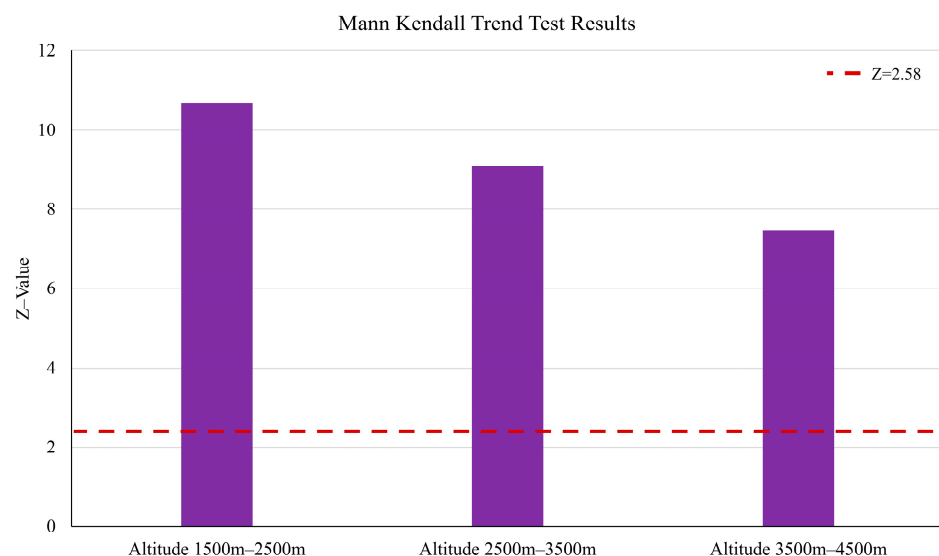


Figure 3. M–K test results of oxygen content at different altitude gradients.

The results of the Mann–Kendall trend test showed that for the low-elevation gradient (1500–2500 m), $Z = 10.68$ ($p < 0.01$); for the mid-elevation gradient (2500–3500 m), $Z = 9.08$ ($p < 0.01$); and for the high-elevation gradient (3500–4500 m), $Z = 7.45$ ($p < 0.01$). All values were significantly greater than the critical threshold of $Z = 2.58$, indicating a significant upward trend in oxygen content across all elevation gradients during the vegetation growing season. Among them, the trend was strongest at low elevations, followed by mid elevations, and relatively weaker at high elevations. These results further confirm the conclusion that the rate of increase in oxygen content is faster at lower elevations during the growing season.

3.2. Variation in Fluctuation Intensity of Oxygen Content Across Different Altitudinal Gradients

To reveal differences in the stability of oxygen content among altitudinal gradients during the vegetation growing season, four statistical indicators—standard deviation (SD),

coefficient of variation (CV), range, and interquartile range (IQR)—were used to analyze the monthly fluctuation intensity of oxygen content for the 1500–2500 m, 2500–3500 m, and 3500–4500 m elevation ranges (Figure 4).

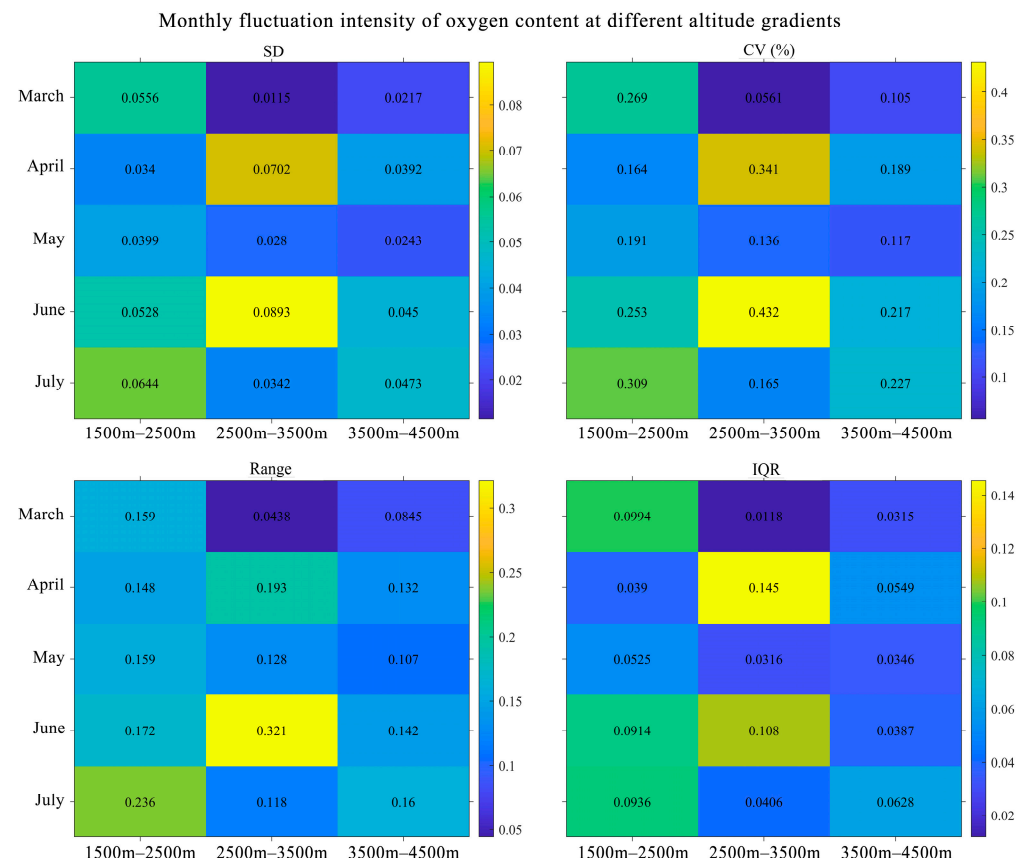


Figure 4. Monthly fluctuation intensity of oxygen content at different altitude gradients.

In terms of standard deviation (SD), the low-elevation gradient (1500–2500 m) reached its maximum in July (0.0644). The mid-elevation gradient (2500–3500 m) peaked in June (0.0893) and showed a secondary high value in April (0.0702). The high-elevation gradient (3500–4500 m) remained relatively stable, without any obvious extreme peaks.

The results of the coefficient of variation (CV) analysis were largely consistent with the SD trends. At the 2500–3500 m gradient, the CV value in June (0.432) was the highest, significantly exceeding that of the other gradients in the same month, indicating the strongest relative variability in oxygen content during this period. The low-elevation gradient showed higher CV values in March (0.269) and July (0.309), while the high-elevation gradient maintained stability throughout the growing season.

For range, which reflects the absolute difference between the maximum and minimum values, the results showed that the low-elevation gradient reached its maximum in July (0.236), whereas the mid-elevation gradient peaked in June (0.321). Although the high-elevation gradient generally exhibited smaller ranges, a noticeable increase was observed in July (0.160).

The interquartile range (IQR), representing the dispersion of the central 50% of the data, indicated that the low-elevation gradient had relatively high values in March (0.0994) and July (0.0936), reflecting more evident fluctuations in early spring and midsummer. The mid-elevation gradient recorded larger IQR values in April (0.145) and June (0.108), while the high-elevation gradient showed small IQR fluctuations throughout, indicating higher stability.

Taken together, the analysis of the four indicators revealed clear spatial differences in the fluctuation intensity of oxygen content. The low-elevation gradient exhibited generally larger fluctuations, particularly in summer; the mid-elevation gradient displayed pronounced peaks in specific months (June); and the high-elevation gradient remained relatively stable, with some enhancement in midsummer.

Further comparison using box plots (Figure 5) provided additional insight into the distributional characteristics of oxygen content across altitudinal gradients during the growing season. Combined with the monthly fluctuation analysis, results showed that differences existed not only in mean oxygen levels but also in fluctuation intensity and stability. The box plots indicated that the 1500–2500 m gradient had the highest median and the widest interquartile range, reflecting higher oxygen levels but greater variability. The 2500–3500 m gradient had the lowest median and the narrowest interquartile range, suggesting lower but more stable oxygen levels. The 3500–4500 m gradient's median fell between the other two, with moderate variability.

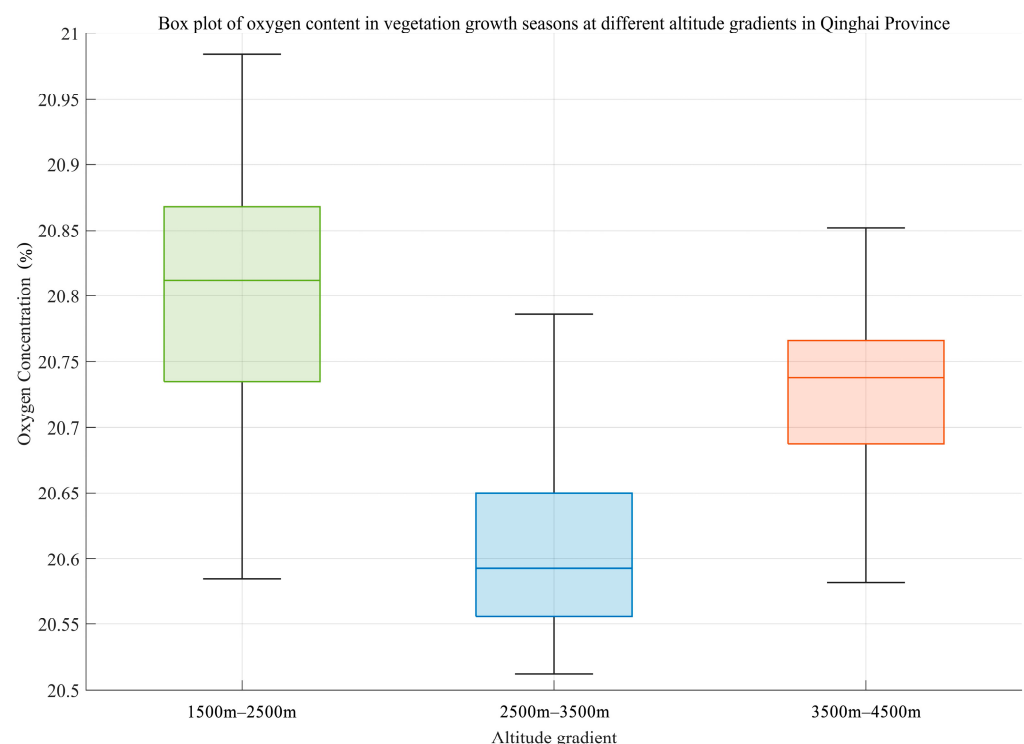


Figure 5. Box plot of oxygen content in vegetation growth seasons at different altitude gradients in Qinghai Province.

The monthly fluctuation heatmaps further revealed the temporal dynamics of these differences: the low-altitude gradient showed pronounced fluctuations in March and July, the mid-altitude gradient peaked sharply in June, and the high-altitude gradient remained stable except for a modest increase in July. Results from SD, CV, range, and IQR were highly consistent, demonstrating that fluctuation intensity is influenced by both altitudinal differences and seasonal patterns—being generally higher in early spring and midsummer, and relatively stable from late spring to early summer.

3.3. Kernel Density Estimation and Difference Analysis of Oxygen Content Across Elevation Gradients

To further elucidate the probability distribution characteristics of oxygen content at different altitudinal gradients, KDE was applied to fit smoothed distributions for the vegetation growing season (March–September) across the 1500–2500 m, 2500–3500 m, and

3500–4500 m elevation ranges. Figure 6 shows the KDE curves of oxygen content for the three elevation gradients during the vegetation growing season (March–July). Compared with traditional histograms, KDE can depict continuous probability density distributions without relying on fixed binning, making it more suitable for capturing subtle variations and potential multimodal structures in oxygen content.

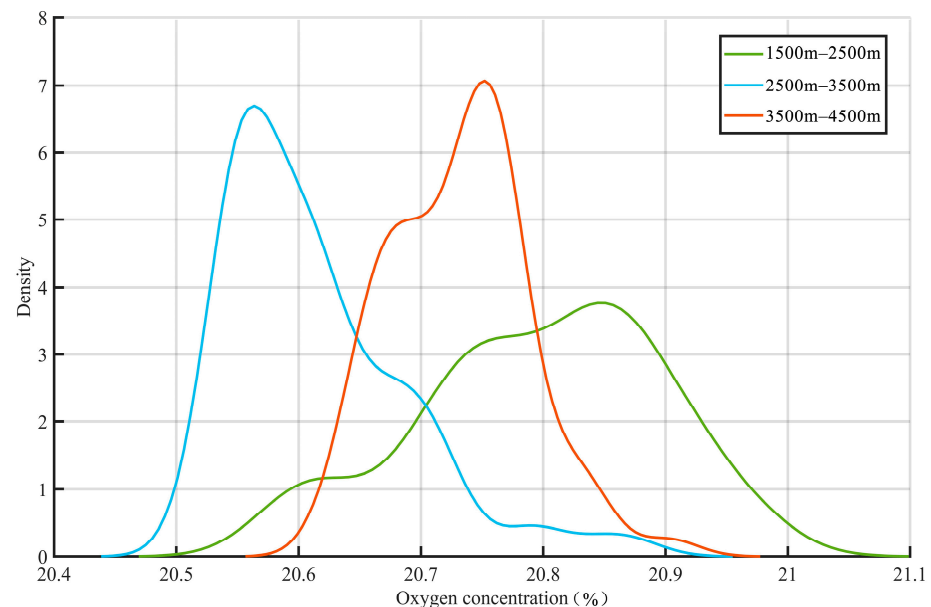


Figure 6. Estimation of nuclear density based on oxygen content gradient at different altitudes.

Overall, the KDE curves for the three altitudinal gradients exhibited unimodal or near-unimodal patterns, but their peak positions and distribution widths differed markedly. For the low-altitude gradient (1500–2500 m), the peak occurred at approximately 20.85, with a relatively long extension on the right tail, indicating a slight right skewness. This suggests that oxygen content is generally higher at this gradient, but occasional periods with even higher oxygen levels occur. The mid-altitude gradient (2500–3500 m) exhibited the most concentrated peak, around 20.55, with a steep curve and narrow distribution, reflecting high stability and low variability in oxygen content. The high-altitude gradient (3500–4500 m) peaked near 20.75, with a relatively flat curve and extended tails on both sides, indicating a moderate oxygen level but higher dispersion, possibly due to rapid temperature changes, large air pressure fluctuations, and diverse vegetation types at high elevations.

A comparison of distribution widths showed that the density curve was narrowest at the mid-elevation gradient, while the low-elevation gradient exhibited the widest distribution. Moreover, the tails of the distributions at low and high elevations displayed a certain degree of overlap. The KDE results further revealed the relationship between oxygen content distribution characteristics and ecological stability across different elevations.

To examine the statistical significance of differences in oxygen content distributions across elevation gradients, this study employed the nonparametric Kruskal–Wallis test. This method does not rely on the assumption of normality and is suitable for ecological data where sample distributions are unbalanced and homogeneity of variance is difficult to satisfy. The post hoc multiple comparison results (Table 1) showed that differences among the three elevation gradients were all statistically significant. Specifically, the differences between low and mid elevations, as well as between low and high elevations, were highly significant (adjusted $p < 0.001$), and the difference between mid and high elevations was also significant (adjusted $p < 0.001$). These results indicate that during the vegetation growing

season (March–September), the mean oxygen content distributions differed significantly across the three elevation ranges.

Table 1. Post hoc multiple comparison results.

Comparison	Mean Rank Difference	Lower CI	Upper CI	<i>p</i> -Value	Conclusion ($\alpha = 0.05$)
1500–2500 m vs. 2500–3500 m	199.92	165.65	234.19	0	Significant
1500–2500 m vs. 3500–4500 m	64.628	30.357	98.898	2.01×10^{-5}	Significant
2500–3500 m vs. 3500–4500 m	−135.29	−169.56	−101.02	0	Significant

To further identify the sources of these differences, post hoc multiple comparisons were conducted. The results are shown in Table 1 below.

4. Discussion

This study demonstrates that during the vegetation growing season in Qinghai Province, oxygen content exhibited the largest increase at low elevations, followed by mid elevations, while high elevations showed relatively moderate changes, indicating a pronounced elevational differentiation pattern.

This study shows that oxygen content during the vegetation growing season in Qinghai Province increased most at low elevations, moderately at mid elevations, and least at high elevations, reflecting a clear elevational differentiation. Previous studies have shown that spatiotemporal differences in oxygen content on the Qinghai–Tibet Plateau are jointly controlled by elevation, vegetation cover, and 500 hPa temperature, with the contribution rates of vegetation, temperature, and elevation estimated at +33.1%, +28.5%, and +3.9% for relative oxygen content. Using the ideal gas law, the absolute oxygen content was further calculated, and the three factors explained 78.9% of the total variance, with the contribution rates of elevation, vegetation, and temperature estimated at +45.9%, +18.5%, and +14.5%, respectively [4]. Our results are consistent with these findings, as the larger increase at low elevations can be attributed to higher temperatures and enhanced vegetation photosynthesis, which prolong the growing season and promote oxygen enrichment [52]. Similarly, previous studies quantified the contribution of vegetation to near-surface oxygen concentration at 16.7–24.5%, aligning well with the pronounced role of vegetation productivity observed in our study [53]. The recent rise in normalized difference vegetation index (NDVI) across the Plateau further supports this mechanism [54], suggesting that vegetation growth under warming conditions is a key driver of oxygen enrichment. By focusing on Qinghai Province, our analysis provides more refined evidence at the provincial scale, complementing previous Plateau-wide assessments with higher spatial resolution.

The results also revealed that oxygen fluctuations were strongest at low elevations and weakest at high elevations, forming a “greater fluctuations at low elevations—smaller fluctuations at high elevations” pattern. This agrees with earlier findings that oxygen responses to meteorological variability and land cover changes are highly heterogeneous across regions [55]. At low elevations, higher temperatures, complex meteorological conditions, and intensive human activities enhance photosynthesis but also amplify short-term variability, which explains the stronger fluctuations observed here. At mid elevations, the pronounced peak in June coincides with rapid seasonal warming and vigorous vegetation growth, indicating higher sensitivity to climatic transitions. In contrast, high-elevation regions, with thinner atmosphere and more homogeneous vegetation, exhibited smaller amplitude changes, consistent with the relative stability reported in previous Plateau studies. Meanwhile, the recent pronounced warming and altered precipitation regimes across the Plateau have added complexity to regional vegetation dynamics and oxygen

distributions [56]. These fluctuations are not only ecologically significant but may also exert far-reaching impacts on human and animal health risks, ecosystem functioning, and atmospheric processes on the Plateau. At the same time, the comparative results indicate that while the overall elevational gradient explains broad differences, local ecological and climatic processes add further variability, thereby providing a more nuanced understanding of oxygen dynamics at finer spatial scales.

Several limitations of this study should be acknowledged. First, the observation period covered only two growing seasons (2022–2023), which constrains the temporal scale and limits the ability to capture long-term trends. Longer-term continuous monitoring would help identify robust patterns under ongoing climate warming and improve the extrapolation of conclusions. Second, the study did not explicitly account for meteorological variables (e.g., wind speed, humidity) or anthropogenic disturbances, which may partially affect the spatiotemporal fluctuations of oxygen content. Third, the spatial distribution of observation sites was restricted, leaving some heterogeneity in complex terrains under-represented. Future research could proceed in several directions: (i) combining long-term monitoring data to assess cumulative effects of climate warming and ecological changes on oxygen dynamics and to build more reliable predictive models; (ii) integrating multi-source remote sensing data and ecological models to explore coupling mechanisms between oxygen content, vegetation productivity, and carbon cycling; (iii) investigating potential impacts of oxygen variability on human health risks and ecosystem functions, thereby providing scientific support for public health and ecological management; and (iv) extending analyses to multiple years with year-round monitoring, including physiological and soil respiration drivers, to better understand the underlying mechanisms of oxygen variability on the Plateau.

In terms of methodology, nonparametric statistical approaches played an important role in this study. Both the Mann–Kendall test and the Kruskal–Wallis test do not rely on the assumption of normality and are capable of handling unbalanced and non-normal environmental monitoring data, thereby ensuring the robustness of the results. However, nonparametric methods have certain limitations in explaining causal mechanisms. Future research could integrate parametric models (e.g., multiple regression or structural equation modeling) to enhance explanatory power while maintaining robustness. Overall, the complementary application of parametric and nonparametric methods will facilitate a more comprehensive understanding of the dynamic patterns of oxygen content.

5. Conclusions

This study revealed pronounced elevational differentiation of near-surface oxygen content during the vegetation growing season in Qinghai Province, leading to the following main conclusions:

- (1) Temporal trends of oxygen content. Across the entire growing season, near-surface oxygen content at all three elevation gradients exhibited significant upward trends. The increase was largest at low elevations (1500–2500 m), moderate at mid elevations (2500–3500 m), and relatively weak at high elevations (3500–4500 m). This indicates that elevation gradients strongly influence the temporal rate of oxygen change.
- (2) Spatial differentiation of fluctuation intensity. The three elevation gradients displayed clear differences in stability. Oxygen content at low elevations, though higher in absolute value, showed the greatest fluctuations; mid elevations exhibited the most intense fluctuations in June; while high elevations were generally stable, with some enhancement in midsummer. These differences reflect the differentiated influences of climatic conditions and ecological processes across altitudinal belts.

- (3) Distributional features and statistical significance. Kernel density estimation showed that low elevations had wider distributions with heavier tails, mid elevations displayed the most concentrated distributions with the lowest variability, and high elevations fell in between. Results of the Kruskal–Wallis test further confirmed highly significant differences among the three elevation gradients, verifying that elevation is a key factor driving the spatial differentiation of oxygen content.

This study reveals consistent patterns of oxygen dynamics across plateau gradients under climate warming and highlights their value as indicators of ecosystem resilience and health risks. Despite being limited to the 2022–2023 growing seasons, station coverage, and correlational analysis, the findings provide new evidence on plateau oxygen cycling and practical references for health risk assessment and ecological management. Future research should incorporate multi-year, year-round observations and physiological drivers to clarify underlying mechanisms. As climate change intensifies, advancing our understanding of oxygen dynamics will be crucial for strengthening human adaptation and high-altitude ecosystem resilience, laying a foundation for more robust management strategies.

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