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UAV LiDAR-Based Morphological Measurement of Caragana tibetica Nebkhas in the Qinghai Gonghe Basin: Postprint

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Abstract

UAV LiDAR technology was employed to measure the morphological parameters, base area, and volume of 300 Caragana tibetica shrub coppice dunes on the west side of Longyangxia Reservoir in the Gonghe Basin, aiming to evaluate the applicability of various formulas from the literature for estimating the base area and volume of shrub coppice dunes and analyze the underlying reasons. The results indicate: (1) UAV LiDAR can precisely measure the morphology of Caragana tibetica shrub coppice dunes, with average relative errors of the long axis (L), short axis (W), and height (H) being 0.70%, 1.13%, and -1.67%, respectively, and their corresponding root mean square errors being 0.02 m, 0.03 m, and 0.03 m; the root mean square errors of planar accuracy and three-dimensional accuracy are 0.03 m and 0.04 m, respectively, all meeting the accuracy requirements. (2) The morphological parameters such as long axis, short axis, and height of Caragana tibetica shrub coppice dunes exhibit small variation ranges, with coefficients of variation between 0.26 and 0.33. The morphological parameters are significantly correlated with each other ($P<0.01$), indicating that the morphology of shrub coppice dunes results from synergistic growth in length, width, and height. Additionally, the crust, dead shrubs, and wind erosion pits on the surface of shrub coppice dunes all indicate that the dunes have entered the decline stage from the mature stage. (3) The total relative errors of the base area formulas $\pi[(L+W)/4]2$, $\pi LW/4$, and $LW/2$ for Caragana tibetica shrub coppice dunes are -0.79%, -1.26%, and -37.14%, respectively, with formulas $\pi[(L+W)/4]2$ and $\pi LW/4$ being suitable for this study area. The total relative errors of the volume formulas $3\pi LWH/32$, $\pi LWH/12$, $LWH/6$, $\pi H\{[3(L+W)/4]2+H2\}/6$, and $\pi LWH/6$ are -6.15%, -16.58%, -46.89%, 59.14%, and 66.83%, respectively; the modified volume formula $\pi LWH/10$ has a total relative error of 0.10% and low dispersion, making it more suitable for this study area. In summary, when estimating the base area and volume of

shrub coppice dunes, it is necessary to simultaneously consider the influences of vegetation type, development stage, habitat, or sand source richness, thereby selecting appropriate estimation methods based on site-specific conditions.

Full Text

Morphological Calculation of *Caragana tibetica* Nebkhas Based on UAV LiDAR Technology in Gonghe Basin, Qinghai Province

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Abstract

This study employed unmanned aerial vehicle (UAV) LiDAR technology to measure the morphological parameters, base area, and volume of 300 *Caragana tibetica* nebkhas located west of the Longyangxia Reservoir in the Gonghe Basin, Qinghai Province. The objective was to evaluate the applicability of various estimation formulas for nebkha base area and volume reported in the literature and to analyze the underlying reasons for their performance. The results demonstrate: (1) UAV LiDAR enables precise measurement of *C. tibetica* nebkha morphology, achieving average relative errors of 0.70%, 1.13%, and -1.67% for the length axis (L), width axis (W), and height (H), respectively, with corresponding root-mean-square errors (RMSEs) of 0.02 m, 0.03 m, and 0.03 m. The RMSEs for plane and three-dimensional accuracy were 0.03 m and 0.04 m, respectively, meeting all precision requirements. (2) The morphological parameters (L, W, H) of *C. tibetica* nebkhas showed limited variation, with coefficients of variation ranging from 0.26 to 0.33. All parameters exhibited significant correlations ($P < 0.01$), indicating that nebkha morphology results from coordinated growth in length, width, and height. Surface crusts, dead shrubs, and wind erosion pits on the nebkhas further suggest a transition from mature to declining developmental stages. (3) Among base area formulas, $\pi[(L+W)/4]^2$ and $\pi LW/4$ performed well with total relative errors of -0.79% and -1.26%, respectively, making them suitable for this study area. For volume estimation, the modified formula $\pi LWH/10$ yielded the smallest total relative error (0.10%) and low dispersion, proving most appropriate. In contrast, formulas $\pi LWH/6$ and $LWH/6$, derived from ellipsoid and triangular pyramid geometries, respectively, were unsuitable. In summary, estimating nebkha base area and volume requires careful consideration of vegetation type, developmental stage, habitat conditions, and sand source availability to select appropriate methods tailored to local conditions.

Keywords: nebkhas; drone laser point cloud; geometric formula; total relative error

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Nebkhas are typical aeolian landforms formed when sand particles accumulate behind shrub vegetation under wind action. Their morphology, which varies from hemispherical to ellipsoidal or conical shapes with heights ranging from tens of centimeters to over ten meters, is influenced by wind dynamics, vegetation type, and sand source availability. These structures provide suitable habitats for plants and animals while preserving moisture and nutrients, creating favorable conditions for vegetation growth. Consequently, nebkhas serve as important indicators for analyzing local wind erosion and sand fixation processes.

The morphology of nebkhas can be abstracted as mathematical geometric bodies, enabling calculation of base area, profile area, and volume using morphological parameters such as length axis, width axis, and height. In plan view, most nebkhas project as elliptical shapes resembling half-ellipsoids, allowing area and volume estimation through modified elliptical and ellipsoidal formulas. However, due to variations in habitat, vegetation type, and developmental stage, researchers have proposed multiple formulas for estimating nebkha base area and volume (Table 1), which can differ by several orders of magnitude. This necessitates critical evaluation of their applicability.

Precise measurement of morphological parameters is essential for validating these formulas. Traditional field surveys involve establishing sample plots along transects and measuring nebkhas using tape measures and compasses, which is time-consuming, costly, and prone to error. While remote sensing and Google Earth imagery can study nebkha distribution and planar morphology, retrieving height information remains challenging and often lacks precision. UAV oblique photogrammetry can transform two-dimensional imagery into three-dimensional measurements, but it struggles to separate shrubs from sand masses, introducing height measurement errors. UAV LiDAR technology offers significant potential for accurately obtaining nebkha height information.

This study focuses on *Caragana tibetica* nebkhas in the Gonghe Basin of Qinghai Province, combining UAV LiDAR measurements with Matlab-based Aeolian-Peak tools to precisely determine true nebkha heights and volumes. The research systematically analyzes the morphological characteristics of these nebkhas and evaluates the applicability of existing volume estimation formulas.

1.1 Study Area Overview

The Gonghe Basin in Qinghai Province (35°27 –36°56 N, 98°46 –101°22 E) is located on the northeastern edge of the Tibetan Plateau and the northwestern margin of the Asian monsoon region. Surrounded by mountains, the basin' s elevation decreases gradually from northwest to southeast, covering a total area of 13,800 km^2. The region experiences a cold, arid to semi-arid climate with an average annual temperature of 0.7–6.3°C, significant temperature variations, and abundant sunshine. Mean annual precipitation is 324.7 mm, while evaporation reaches 1,684.5 mm. Vegetation includes *Achnatherum splendens*, *Stellera chamaejasme*, and *Salsola collina*. Due to climate change and human activities since the early 21st century, lightly and moderately desertified areas in the basin have increased by 584.33 km^2 and 215.74 km^2, respectively, providing material conditions for *C. tibetica* nebkha development. The study area features 连片分布的 *C. tibetica* nebkhas with relatively uniform sizes, predominantly in the mature to declining developmental stages [Figure 1: see original paper].

1.2 Data Acquisition and Processing

Field investigations of *C. tibetica* nebkha morphology were conducted in May 2023. A DJI M300 RTK UAV equipped with a LiDAR sensor was used to acquire orthoimages and laser point cloud data of the nebkhas. The morphological parameters (length axis, width axis, base area, height, and volume) were extracted using LiDAR technology. For validation, length axes were measured along the main wind direction and width axes perpendicular to it using tape measures. Heights at both ends of the axes were measured with steel rulers and averaged.

For height extraction, UAV LiDAR point cloud data were processed in DJI Terra to generate DEMs with 0.1 m resolution. These were exported in Global Mapper format and converted to ASCII files in ArcGIS Pro, where nebkha bases and length axes were digitized. Zonal statistics identified maximum and minimum heights. The length axis was converted to points at 0.1 m intervals using ArcGIS Pro' s "points along line" tool, and DEM values were extracted to these points. In the AeolianPeak Matlab tool, maximum and minimum height values were sequentially selected along each profile. The difference between these values represents shrub height, which was subtracted from the total nebkha height to obtain the sand-only height [Figure 2: see original paper].

Base area was calculated using ArcGIS Pro' s geodesic area calculation tool with Python rounding to six decimal places. Volume was computed using the surface volume tool, which integrates the point cloud file with a baseline adjusted for shrub height.

1.3.1 LiDAR Data Precision Evaluation

Three-dimensional model precision can be evaluated through plane accuracy, height accuracy, 3D accuracy, orthoimage precision, model detail, and texture detail. This study compared field-measured length axes, width axes, and heights with corresponding values extracted from LiDAR data. RMSE was calculated as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

where d_i is the difference between the ith measured value and LiDAR-extracted value. Plane RMSE ($\text{RMSE}_{\text{plane}}$) and 3D RMSE ($\text{RMSE}_{\text{3D}}$) were computed as:

$$\text{RMSE}_{\text{plane}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[(L_i' - L_i)^2 + (W_i' - W_i)^2]}$$

$$\text{RMSE}_{\text{3D}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[(L_i' - L_i)^2 + (W_i' - W_i)^2 + (H_i' - H_i)^2]}$$

where L_i, W_i, H_i and L_i', W_i', H_i' are the measured and LiDAR-extracted values for the ith nebkha.

1.3.2 Geometric Formula Precision Evaluation

To assess formula accuracy, 30 nebkhas of varying sizes were randomly selected. Total relative error (TRE) and variance (σ) were calculated by comparing measured and computed values:

$$\text{TRE} = \frac{\sum_{i=1}^{n}(X_i' - X_i)}{\sum_{i=1}^{n} X_i} \times 100\%$$

$$\sigma = \frac{1}{n}\sum_{i=1}^{n}(X_i' - X_i)^2$$

where X_i' and X_i are the computed and measured values for the ith formula.

2.1 LiDAR Data Precision Verification

Precision was evaluated for 30 *C. tibetica* nebkhas . Relative errors ranged from -7.89% to 9.80% for length axis, -0.28% to 1.46% for width axis, and -0.63% to 4.10% for height, with average relative errors of 0.70%, 1.13%, and -1.67%, respectively. RMSEs were 0.02 m, 0.03 m, and 0.03 m for length, width, and height, respectively, with plane and 3D RMSEs of 0.03 m and 0.04 m. These statistics confirm that the LiDAR data meet precision requirements.

2.2.1 Statistical Analysis of Nebkha Morphological Parameters

The *C. tibetica* shrub coverage on nebkha surfaces showed little variation, indicating mature to declining stages. The nebkhas exhibited spherical-crown shapes with rounded tops and gentle slopes [Figure 1: see original paper]. Plan views were elliptical, while side profiles displayed arch-like characteristics.

Measurements of 300 nebkhas revealed length axes of 0.68–2.49 m (mean: 1.19 m), width axes of 0.58–2.69 m (mean: 1.20 m), and heights of 0.11–1.25 m (mean: 0.51 m). Coefficients of variation were small (0.26–0.33), indicating uniform development and relatively small sizes. Profile areas ranged from 0.29–1.34 m^2 (mean: 0.60 m^2), while volumes varied from 0.05–1.89 m^3 (mean: 0.42 m^3), reflecting modest sand-fixing capacity.

2.2.2 Correlation Analysis of Morphological Parameters

All morphological parameters showed significant correlations ($P < 0.01$) , demonstrating coordinated growth and interdependence. Length axis correlated strongly with width axis ($R^2 = 0.85$) and height ($R^2 = 0.61$), while width axis correlated with height ($R^2 = 0.68$). This linear relationship between length and width axes indicates synchronized expansion during wind-driven development [Figure 3: see original paper].

Profile area and volume followed a power function relationship, revealing non-linear growth dynamics. Initially, profile area increased faster than volume, but after reaching a threshold, volume growth accelerated. Height correlated linearly with horizontal scale but showed a quadratic relationship with base area, suggesting that height growth slows as base area expands, eventually stabilizing.

2.3 Evaluation of Nebkha Geometric Formulas

Thirty nebkhas were tested to evaluate formula accuracy . For base area, formulas $\pi[(L+W)/4]^2$, $\pi LW/4$, and LW/2 yielded total relative errors of -0.79%, -1.26%, and -37.14%, respectively. The first two formulas, based on elliptical geometry, proved suitable for this study area, while the triangular-based LW/2 was inappropriate.

For volume, formulas $3\pi LWH/32$, $\pi LWH/12$, LWH/6, $\pi H\{[3(L+W)/4]^2+H^2\}/6$, and $\pi LWH/6$ produced total relative errors of -6.15%, -16.58%, -46.89%, 59.14%, and 66.83%, respectively. The modified formula $\pi LWH/10$ achieved the smallest total relative error (0.10%) and lowest variance (0.0656 m^3), making it optimal for this region. Formulas $\pi LWH/6$ and LWH/6, derived from ellipsoid and triangular pyramid geometries, respectively, were unsuitable [FIGURE:4, FIGURE:5].

Discussion

Caragana tibetica nebkhas in the study area exhibited regional morphological similarity, with variation coefficients (0.26–0.33) slightly lower than those reported for stable-stage nebkhas in Damaoqi, Inner Mongolia (0.1–0.4). The morphological parameters showed significant correlations, consistent with previous research on nebkha development. The finding that profile area initially grows faster than volume, with the relationship reversing at a certain stage, reflects initial rapid vegetation growth followed by enhanced sand interception as plants mature.

Formula suitability is closely related to nebkha morphology. The high accuracy of $\pi[(L+W)/4]^2$ and $\pi LW/4$ reflects their elliptical base geometry. In contrast, LW/2 corresponds to severely wind-eroded, triangle-shaped nebkhas observed in Alxa' s gobi regions. Volume formulas $\pi LWH/6$ and LWH/6, based on ellipsoid and triangular pyramid geometries, were unsuitable because the study area' s nebkhas are flattened ellipsoids due to sparse branching and low height. The optimal $\pi LWH/10$ formula was derived through least-squares fitting, reducing the total relative error to 0.10%.

Habitat conditions significantly influence nebkha morphology. In the study area, relatively flat terrain with moderate sand availability resulted in moderately developed nebkhas. In contrast, western desert regions with abundant sand sources produce larger nebkhas, while grassland areas with limited sand produce smaller ones. The mature-to-declining developmental stage, characterized by reduced sand supply, declining water tables, or shrub mortality, further contributes to flattened morphologies requiring formula modification.

Conclusions

1. UAV LiDAR technology enables precise measurement of *C. tibetica* nebkha morphology, achieving average relative errors of 0.70%, 1.13%, and -1.67% for length axis, width axis, and height, respectively, with corresponding RMSEs of 0.02 m, 0.03 m, and 0.03 m. Plane and 3D RMSEs of 0.03 m and 0.04 m satisfy precision requirements.
2. Morphological parameters showed limited variation (coefficients: 0.26-0.33) and significant correlations ($P < 0.01$), indicating coordinated growth. The power function relationship between profile area and volume, combined with linear and quadratic relationships between height and horizontal scale/base area, demonstrates the transition from mature to declining developmental stages.
3. Base area formulas $\pi[(L+W)/4]^2$ and $\pi LW/4$ are suitable for this study area, while the modified volume formula $\pi LWH/10$ (total relative error: 0.10%) provides the best fit. Formulas LW/2 and LWH/6, based on triangular geometries, are inappropriate for triangle-shaped, severely eroded nebkhas. Volume formulas $\pi LWH/6$ and $\pi LWH/12$, derived from ellipsoid geometry, also proved unsuitable. Therefore, selecting appropriate formulas requires simultaneous consideration of vegetation type, developmental stage, habitat, and sand source availability.

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