

Dividing the transit wind speeds into intervals as a favorable methodology for analyzing the relationship between wind speed and the aerodynamic impedance of vegetation in semiarid grasslands postprint

Authors: Li Ruishen, PEI Haifeng, ZHANG Shengwei, Fengming Li, LIN Xi, WANG Shuai1, YANG Lin

Date: 2023-08-15T00:00:00+00:00

Abstract

In grassland ecosystems, the aerodynamic roughness (Z_0) and frictional wind speed (u) contribute to the aerodynamic impedance of the grassland canopy. Thus, they are often used in the studies of wind erosion and evapotranspiration. However, the effect of wind speed and grazing measures on the aerodynamic impedance of the grassland canopy has received less analysis. In this study, we monitored wind speeds at multiple heights in grazed and grazing-prohibited grasslands for 1 month in 2021, determined the transit wind speed at 2.0 m height by comparing wind speed differences at the same height in both grasslands, and divided these transit wind speeds at intervals of 2.0 m/s to analyze the effect of the transit wind speed on the relationship among Z_0 , u , and wind speed within the grassland canopy. The results showed that dividing the transit wind speeds into intervals has a positive effect on the logarithmic fit of the wind speed profile. After dividing the transit wind speeds into intervals, the wind speed at 0.1 m height ($V_{0.1}$) gradually decreased with the increase of Z_0 , exhibiting three distinct stages: a sharp change zone, a steady change zone, and a flat zone; while the overall trend of u^* increased first and then decreased with the increase of $V_{0.1}$. Dividing the transit wind speeds into intervals improved the fitting relationship between Z_0 and $V_{0.1}$ and changed their fitting functions in grazed and grazing-prohibited grasslands. According to the computational fluid dynamic results, we found that the number of tall-stature plants has a more significant effect on windproof capacity than their height. The results of this study contribute to a better understanding of the relationship between wind speed and the aerodynamic impedance of vegetation in grassland environments.

Full Text

Preamble

Journal of Arid Land (2023) 15(8): 887-900

<https://doi.org/10.1007/s40333-023-0102-8>

Science Press & Springer-Verlag

Dividing the Transit Wind Speeds into Intervals as a Favorable Methodology for Analyzing the Relationship between Wind Speed and the Aerodynamic Impedance of Vegetation in Semiarid Grasslands

LI Ruishen¹, PEI Haifeng¹, ZHANG Shengwei^{1,2,3*}, LI Fengming⁴, LIN Xi¹, WANG Shuai¹, YANG Lin^{1}

¹ College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China

² Key Laboratory of Water Resources Protection and Utilization of Inner Mongolia Autonomous Region, Hohhot 010018, China

³ Autonomous Region Collaborative Innovation Center for Integrated Management of Water Resources and Water Environment in the Inner Mongolia Reaches of the Yellow River, Hohhot 010018, China

⁴ Inner Mongolia Autonomous Region Management Center of Sanshengong Hydro-junction in the Yellow River, Bayannur 015200, China

Abstract: In grassland ecosystems, aerodynamic roughness (Z_0) and frictional wind speed (u) contribute to the aerodynamic impedance of the grassland canopy and are frequently employed in studies of wind erosion and evapotranspiration. However, the effects of wind speed and grazing practices on the aerodynamic impedance of grassland canopies have received limited analytical attention. In this study, we monitored wind speeds at multiple heights in grazed and grazing-prohibited grasslands for one month in 2021, determined the transit wind speed at 2.0 m height by comparing wind speed differences at the same height in both grasslands, and divided these transit wind speeds into 2.0 m/s intervals to analyze how transit wind speed influences the relationships among Z_0 , u , and wind speed within the grassland canopy. The results demonstrated that dividing transit wind speeds into intervals positively affects the logarithmic fit of the wind speed profile. After interval division, wind speed at 0.1 m height ($V_{0.1}$) gradually decreased with increasing Z_0 , exhibiting three distinct stages: a sharp change zone, a steady change zone, and a flat zone, while the overall trend of u^* initially increased then decreased with increasing $V_{0.1}$. Interval division improved the fitting relationship between Z_0 and $V_{0.1}$ and altered their fitting functions in grazed versus grazing-prohibited grasslands. Computational fluid dynamics results revealed that the number of tall-stature plants has a more significant effect on windproof capacity than their height. These findings contribute to a better understanding of the relationship between wind speed and vegetation aerodynamic impedance in grassland environments.

Keywords: transit wind speeds; frictional wind speed; aerodynamic roughness; computational fluid dynamics (CFD); grazed grassland; grazing-prohibited grassland

Citation: LI Ruishen, PEI Haifeng, ZHANG Shengwei, LI Fengming, LIN Xi, WANG Shuai, YANG Lin. 2023. Dividing the transit wind speeds into intervals as a favorable methodology for analyzing the relationship between wind speed and the aerodynamic impedance of vegetation in semiarid grasslands. *Journal of Arid Land*, 15(8): 887-900. <https://doi.org/10.1007/s40333-023-0102-8>

*Corresponding author: ZHANG Shengwei (E-mail: zsw@imau.edu.cn)

Received 2022-10-08; revised 2023-02-14; accepted 2023-02-27

© The Author(s) 2023

1 Introduction

The vegetation of typical grasslands in northern China is characteristically short, sparse, and vulnerable to degradation. Grazing disturbs the grassland canopy (Jäschke et al., 2020), thereby altering surface aerodynamic impedance characteristics. The amount of standing grass residue represents a key factor affecting surface resistance to wind erosion during the non-growing season (Pi et al., 2020). Aerodynamic characteristics of grassland canopies are crucial for understanding fundamental processes of soil physicochemical property changes (Rauber et al., 2021) and soil-atmosphere gas exchange (Haghighi and Or, 2015). Consequently, research on grassland canopy aerodynamic characteristics during the non-growing season can inform climate models, wind meteorology, agro-pastoral production, and erosion hazard studies in pastoral regions (Levin et al., 2008).

Wind speed profile observations in grasslands effectively describe the interrelationship between vegetation and airflow (Zhang et al., 2012). Different climatic characteristics (Yu et al., 2018), vegetation distributions, and leaf morphologies constitute key factors affecting wind speed profiles (Luo et al., 2020). Aerodynamic roughness (Z_0) of vegetation and frictional wind speed (u) are derived from wind speed profiles and have been used to explain vegetation-aerodynamic impedance relationships under neutral atmospheric conditions. Z_0 may be understood as the height above ground where wind speed reaches 0.0 m/s, while u represents the shear effect of wind on the ground surface (Stull, 1988). Extensive analyses of both Z_0 and u^* have been conducted using field and indoor wind tunnel models. Grassland canopy wind resistance manifests primarily through two mechanisms: branch deformation energy dissipation and wind flow redistribution. Wind alters vegetation morphology (Liu et al., 2021), and in grasslands, taller vegetation experiences greater wind-induced bending and consequently higher rates of decline in windproof capacity. The flexibility and consequent bending of plants due to wind differ among species with similar aerodynamic characteristics (Kinugasa et al., 2021). Aerodynamic characteristics of grassland

canopies may also be influenced by the abundance of particularly robust grass species. The mechanical strength of blades and mass per unit area determine vegetation deformation (Onoda et al., 2011). Overgrazed grasslands exhibit considerably reduced wind resistance due to low leaf density and plant height. Grazing effects on plants modify wind impacts on the grassland canopy, and vegetation consumed by animals in semiarid grasslands is difficult to restore. We can leverage the consequences of long-term vegetation changes induced by grazing to better understand linkages between grassland canopies and wind.

Most previous studies have focused on wind rather than vegetation impedance (Fu et al., 2019; Liu et al., 2021; Xiong et al., 2021), and the effects of increasing wind speed on Z_0 and u^* have received limited attention. Modeling can identify factors affecting aerodynamic characteristics because field observations may miss certain details of variability. Field monitoring of wind flow fields is time-consuming and labor-intensive, whereas computational fluid dynamics (CFD) offers an effective and widely used research method. CFD can simplify complex environmental conditions to analyze wind flow fields through momentum and energy balance equations, such as in studies of artificial windproof measures affecting wind erosion and gravel transport (Xin et al., 2021). Numerical simulation methods can replace aerodynamic monitoring of tall trees (Zhang et al., 2022) while accurately representing wind and sand transport properties of shrubs at different locations (Gonzales et al., 2018). In our study area, vegetation is short and sparse, making it difficult to determine the relationship between vegetation and wind speed. CFD can bridge this observation scale gap while facilitating quantification of the wind speed-vegetation relationship.

In this study, we monitored vertical wind speed profiles in selected grazing-prohibited and grazed grasslands at Eritu pasture in Inner Mongolia Autonomous Region, China. We used variance testing to determine the height of transit wind speeds, then divided the range of transit wind speeds into multiple intervals to study grassland canopy aerodynamic characteristics. Additionally, we employed CFD for numerical simulation. Our objectives were to select reasonable aerodynamic characteristic values for prolonged wind action and analyze how Z_0 and u^* within the grassland canopy respond to wind speed.

2.1 Study Area

The study area (42°05' -43°02' N, 114°05' -115°37' E; Fig. 1 [Figure 1: see original paper]) is located in Eritu pasture, Xilin Gol League, east-central Inner Mongolia Autonomous Region, China. The region experiences a mid-temperate semiarid continental climate with four distinct seasons, hot summers and cold winters, an annual average temperature of 1.9°C, and a maximum temperature of 34.9°C. Dominant species include *Artemisia frigida* Willd., *Stipa krylovii* Roshev., *Leymus chinensis* (Trin.) Tzvel., and *Cleistogenes squarrosa* (Trin.) Keng. South and southeast winds predominate, with an annual average wind speed of

4.0 m/s.

Fig. 1 Overview of the study area and experimental apparatus (a) and images of vegetation growth in grazing-prohibited and grazed grasslands (b)

2.2 Experimental Design

To observe wind speeds in grazing-prohibited and grazed grasslands, we conducted experiments from September 15 to October 15, 2021. We grazed wether sheep (2 years old) on the grazed grassland at a stocking rate of 2.45 sheep/hm², creating a heavily grazed condition. Additionally, we established a 30 m × 30 m grazing-prohibited plot within the grazed grassland. The grazing-prohibited area had been fenced for three years prior to the investigation. The distance between grazed and grazing-prohibited plots was only 20 m, facilitating comparison of wind speeds and vegetation characteristics.

2.3 Vegetation Parameters of Grassland

Vegetation constitutes the foundation of experimental conditions in this study. We conducted vegetation surveys in both grazing-prohibited and grazed grasslands, selecting three quadrats in each [Figure 2: see original paper]. Plant species cover within quadrats was estimated using manual visual interpretation, while overall cover was computed from photographic data. Vegetation height was measured with a ruler, and total clump numbers were recorded. Height, cover, and species counts were measured three times each.

We performed vegetation surveys at the beginning and end of the experiment using random sampling methods, excluding rare species. Plants exceeding 10 cm in height were classified as tall-stature plants (TSP), while those below 10 cm were designated short-stature plants (SSP). Only species with cover exceeding 5.00% were counted (Zheng et al., 2020). Due to the long observation period, we used digital cameras to photograph vegetation conditions hourly to continuously record growth status (Alberton et al., 2017). This study presents photos from three time points during the observation period (September 15, October 1, and October 15, 2021; Fig. 1b). Cover values for the grazing-prohibited grassland were 37.55%, 38.09%, and 38.86%, respectively, while grazed grassland cover values were 28.08%, 31.06%, and 30.62%. These values were calculated using the RGB (red, green, and blue) method in Python (Alberton et al., 2017), which provides higher accuracy and continuity. RGB method results were slightly lower than those obtained through manual visual interpretation. Photographic data showed slight cover changes in both treatments during the observation period. Vegetation density was higher in grazing-prohibited grassland, though TSP heights were similar between the two.

Fig. 2 Photos of artificial vegetation survey (a), quadrat (b), and wind speed monitor (c)

Table 1 Vegetation characteristics of grazing-prohibited and grazed grasslands at the beginning and end of the experiment

Note: TSP, tall-stature plant (species >10 cm height); SSP, short-stature plant (species <10 cm height); NPS, number of plant species; CPS, cover degree of plant species; HPS, height of plant species; -, no data. For Artemisia frigida Willd., CPS replaced NPS due to the species being tiny and dense. Values are mean±SD.**

2.4 Numerical Simulation

We performed CFD simulations of wind speed-vegetation interactions using Ansys Fluent 2022 software. Geometric models were developed using measured vegetation data from Table 1, incorporating height and cover degree while ignoring species numbers. The weighted average vegetation model height (ΔH ; cm) was calculated as:

$$\Delta H = \frac{\text{CPS}_{L.chinensis} \times \text{HPS}_{L.chinensis} + \text{CPS}_{C.squarrosa} \times \text{HPS}_{C.squarrosa} + \text{CPS}_{S.krylovii} \times \text{HPS}_{S.krylovii}}{\Delta \text{CPS}}$$

where ΔCPS (%) is the total cover degree of *L. chinensis*, *C. squarrosa*, and *S. krylovii*, including overlapping portions; CPS (%) is cover degree of plant species; and HPS (cm) is height of plant species. Vegetation in the experimental region consists primarily of elongated leaves, a trait noted in our model. The CFD turbulence model employed was k-epsilon, suitable for most conditions. Wall conditions referenced field-measured Z_0 values. We used the Gauss-Seidel iterative method for 500 iterations until results converged to specified accuracy.

2.5 Transit Wind Speeds and Wind Speed Characteristic Values

Wind speeds at heights of 0.1, 0.4, 0.6, 1.2, and 2.0 m above ground were measured using wind cups (RS-FSJT, Renko Measurement and Control Technology Company, Shandong Province, China) in both grazing-prohibited and grazed grasslands. Measurement accuracy was 0.1 m/s with a 20-minute interval. All data were collected via a data logger (CR1000X, Campbell, Utah, USA). Wind speed typically increases with distance from the ground (Stanhill, 1969; de Souza et al., 2016). Analysis of variance revealed no significant difference in wind speed at 2.0 m height ($V_{2.0}$) between treatments, so $V_{2.0}$ was adopted as the transit wind speed. With plant heights ranging from 10-20 cm, wind speed at 0.1 m height ($V_{0.1}$) represented the within-canopy wind speed. To facilitate

analysis of $V_{0.1}$ and grassland aerodynamic characteristics, we selected 2.0 m/s intervals, classifying transit wind speeds into five categories: 0.0–2.0, 2.0–4.0, 4.0–6.0, 6.0–8.0, and 8.0–10.0 m/s.

The logarithmic fitting function between height and wind speed can be derived from the wind speed profile (Stanhill, 1969). To ensure representative profiles and prevent meteorological factors such as temperature and humidity from affecting airflow stability (Du et al., 2017), we selected profiles with coefficient of determination (R^2) > 0.75. The wind speed profile is commonly modeled using the log-profile equation:

$$U_z = A + B \ln(z)$$

where z is height above ground (m); U_z is wind speed at height z (m/s); and A and B are regression coefficients.

The frictional wind speed u^* (m/s), representing shear stress from wind action, is calculated as (Dong et al., 2001):

$$u_* = \frac{U_z K}{\ln\left(\frac{z-d}{Z_0}\right)}$$

where Z_0 is aerodynamic roughness (mm); K is the von Kármán constant (typically 0.4); and d is zero-plane displacement (mm), representing the height of momentum absorption by a single roughness element, calculated as (Li et al., 2015):

$$d = 0.979 \log(\text{HPS}) - 0.154$$

2.6 Screening Method Based on Wind Speed Data for Aerodynamic Roughness (Z_0)

We measured wind speed profiles in grazing-prohibited and grazed grasslands and determined $V_{2.0}$. The data processing flow is illustrated in Figure 3 [Figure 3: see original paper], which facilitates analysis of the Z_0 - u^* relationship.

Fig. 3 Flowchart used in this study for enhancing the relationship between aerodynamic roughness (Z_0) and frictional wind speed (u^*)

3.1 Effect of Transit Wind Speeds on Wind Speed at 0.1 m Height ($V_{0.1}$)

Figure 4 [Figure 4: see original paper] shows that $V_{0.1}$ was related to transit wind speed frequency. For different grazing measures, when transit wind speeds were below 5.0 m/s, their frequency differed significantly between treatments. The $V_{0.1}$ values for 0.0–2.0 and 5.0–8.0 m/s intervals comprised the same transit wind speeds in both grasslands, primarily causing $V_{0.1}$ differences in the 2.0–5.0 m/s range. For example, $V_{0.1}$ for 2.0–4.0 m/s in grazing-prohibited grassland was influenced by transit wind speeds of 8.0–10.0 m/s, indicating that grazing-prohibited grassland more effectively restrains strong transit wind speeds.

Table 2 shows no significant difference in $V_{2.0}$ between treatments. Due to the low grassland canopy, vegetation effects on wind speed gradually decreased with height above ground. Except for the 0.0–2.0 m/s interval, $V_{0.1}$ differed significantly between grazing-prohibited and grazed grasslands at transit wind speeds of 2.0–4.0, 4.0–6.0, 6.0–8.0, and 8.0–10.0 m/s. The logarithmic function R^2 for wind speed profiles was relatively large ($R^2 > 0.85$) but showed a decreasing trend with increasing transit wind speed in grazed grassland. Grassland characteristics and transit wind speed velocity caused these logarithmic fitting changes, which influenced Z_0 calculation. The Z_0 - $V_{0.1}$ fitting relationship showed a decreasing trend in grazing-prohibited grassland, while it increased then decreased in grazed grassland.

Fig. 4 Frequency of different transit wind speeds at wind speed at 0.1 m height ($V_{0.1}$) in grazing-prohibited grassland (a) and grazed grassland (b)

Table 2 Parameters related to the wind speed profile in grazing-prohibited and grazed grasslands

Note: *A* and *B* are regression coefficients from Equation 3. “*” indicates significant difference in wind speed between grazing-prohibited and grazed grassland for the same transit wind speed ($P < 0.05$).

3.2 Effect of Wind Speed on Z_0

As shown in Figure 5 [Figure 5: see original paper], Z_0 in both grazing-prohibited and grazed grasslands tended to decrease with increasing transit wind speeds. Z_0 in grazing-prohibited grassland decreased rapidly at lower transit wind speeds, while Z_0 in grazed grassland decreased rapidly at higher transit wind speeds. At equivalent transit wind speeds, Z_0 was higher in grazing-prohibited grassland.

Z_0 values were concentrated at higher transit wind speeds and decreased as transit wind speeds increased (Fig. 5b–f). $V_{0.1}$ tended to decrease with increasing Z_0 (Fig. 5f). Each transit wind speed interval from 2.0–8.0 m/s exhibited three stages: a sharp change zone, a steady change zone, and a flat zone. The

sharp change zone disappeared at 8.0–10.0 m/s transit wind speed (Fig. 5f), indicating relatively smooth Z_0 variation at higher wind speeds.

We simulated Z_0 as a function of $V_{0.1}$ for both grasslands. Comparing R^2 values reveals that interval division improved the $V_{0.1}$ - Z_0 fitting relationship. A slight R^2 decrease occurred in grazing-prohibited grassland at 0.0–2.0 m/s and in grazed grassland at 8.0–10.0 m/s, possibly due to canopy structure changes, suggesting that interval division may affect the $V_{0.1}$ - Z_0 relationship.

Fig. 5 (a) Relationship between wind speed at 2.0 m height ($V_{2.0}$) and Z_0 ; (b–f) Relationship between Z_0 and $V_{0.1}$ at transit wind speeds of 0.0–2.0, 2.0–4.0, 4.0–6.0, 6.0–8.0, and 8.0–10.0 m/s, respectively. For figures b–f, shaded areas on the right side of the y-axis and upper side of the x-axis show probability densities of $V_{0.1}$ and Z_0 , respectively, while shaded areas inside each figure represent 95% confidence intervals.

Table 3 Z_0 as a function of $V_{0.1}$ for different transit wind speeds

3.3 Effect of Wind Speed on Frictional Wind Speed (u^*)

In both grazing-prohibited and grazed grasslands, u^* increased with transit wind speed [Figure 6: see original paper]. u^* was significantly higher in grazing-prohibited grassland, indicating better wind resistance as wind speed increased.

No significant regular variation occurred between u^* and $V_{0.1}$ at 0.0–2.0 m/s transit wind speed (Fig. 6b). At transit wind speeds of 2.0–4.0, 4.0–6.0, 6.0–8.0, and 8.0–10.0 m/s, the u - $V_{0.1}$ relationship showed an initial increase followed by a decrease (Fig. 6c–f). The clustering degree of $V_{0.1}$ and u decreased with increasing transit wind speed, with this effect more pronounced in grazed grassland.

Fig. 6 (a) Relationship between $V_{2.0}$ and frictional wind speed (u); (b–f) Relationship between $V_{0.1}$ and u at transit wind speeds of 0.0–2.0, 2.0–4.0, 4.0–6.0, 6.0–8.0, and 8.0–10.0 m/s, respectively. For figures b–f, box plot upper and lower limits indicate 75th and 25th percentile values; horizontal lines represent medians; whiskers show maximum and minimum values; scattered points are outliers. Shaded areas represent 95% confidence intervals.

3.4 Effect of Transit Wind Speeds on the Relationship between u^* and Z_0

To explain how transit wind speeds affect the u - Z_0 relationship, we used the ratio of transit wind speed to u (u/u). As shown in Figure 7 [Figure 7: see original paper], Z_0 showed logarithmic decrease with increasing u/u . When u/u^*

exceeded 20, many discrete points appeared, with Z_0 values greater than 1.76 mm and 0.98 mm in grazing-prohibited and grazed grasslands, respectively.

We fitted the Z_0 - u^* relationship using average u^* values after interval division and found Z_0 decreased with increasing u^* (Fig. 7b). In grazing-prohibited grassland, a power function relationship existed between Z_0 and average u^* after interval division, while a linear relationship occurred in grazed grassland.

Fig. 7 (a) Relationship between the ratio of transit wind speeds to u^* (u/u^*) and Z_0 ; (b) Relationship between Z_0 and average u values after dividing transit wind speeds into intervals (0.0-2.0, 2.0-4.0, 4.0-6.0, 6.0-8.0, and 8.0-10.0 m/s)

3.5 Computational Fluid Dynamics (CFD) Simulation of Wind Flow Field

CFD modeling simulated differences in wind flow fields between grazing-prohibited and grazed grasslands using transit wind speeds of 2.0, 5.0, and 10.0 m/s as examples [Figure 8: see original paper]. At 2.0 m/s transit wind speed, both grasslands showed similar effects on $V_{0.1}$ (Fig. 8a and b). The 5.0 m/s transit wind speed significantly increased $V_{0.1}$ in grazed grassland. The 10.0 m/s transit wind speed had a greater overall effect on the wind flow field in grazing-prohibited grassland than in grazed grassland.

This phenomenon indicates that vegetation density is a key factor affecting wind speed profiles. Near the grassland canopy, dense vegetation can divert more wind away from the ground. With increasing height, differences in wind flow fields between grazing-prohibited and grazed grasslands decreased. These results demonstrate that $V_{2.0}$ was minimally influenced by surface vegetation differences, confirming that interval division of transit wind speeds better analyzes vegetation effects on wind speed profiles.

Additionally, we calculated wind flow fields using CFD simulation [Figure 9: see original paper]. Results showed that vegetation's wind-deflecting effect is the primary mechanism for reducing $V_{0.1}$, more evident in grazing-prohibited grassland. As wind speed increased, the windproof effect of grazing-prohibited grassland became more pronounced.

Fig. 8 Front view of CFD simulation at transit wind speeds of 2.0, 5.0, and 10.0 m/s in grazing-prohibited grassland (a-c) and grazed grassland (d-f)

Fig. 9 Top view (at 0.1 m height) of CFD simulation at transit wind speeds of 2.0, 5.0, and 10.0 m/s in grazing-prohibited grassland (a-c) and grazed grassland (d-f). White points indicate geometric model positions in the wind flow field.

4.1 Aerodynamic Effects of Grazing Measures

Vegetation height and density are key factors affecting aerodynamics (Kang et al., 2019). Grazing represents the primary ecological utilization of arid and semiarid grasslands, with livestock trampling and foraging causing vegetation characteristic changes (Jäschke et al., 2020). Heavily grazed grasslands experience community degradation, evidenced by proliferation of short-stature plants (Török et al., 2018). Thus, different grazing measures alter grassland canopy effects on vegetation aerodynamic impedance. In this study, tall-stature plant numbers were significantly higher in grazing-prohibited grassland. Vegetation characteristics differentially affected transit wind speeds. For example, at higher transit wind speeds (8.0–10.0 m/s), maximum Z_0 values were approximately 5.7 mm in grazed grassland and 7.5 mm in grazing-prohibited grassland. Grazing-prohibited grassland exhibited stronger $V_{0.1}$ blocking [Figure 5f: see original paper], primarily due to wind-induced deformation of the grassland canopy top, with dense vegetation in grazing-prohibited grassland showing greater resistance to this deformation (Kinugasa et al., 2021).

CFD results [Figure 8: see original paper] revealed that tall-stature plant number has a more significant effect on windproof capacity than plant height. For sparse grasslands, individual tall-stature plants are particularly important for optimal canopy wind blocking, and wind speed reduction in fine-leaved vegetation depends more on plant number than height, influenced by leaf morphology (Miri et al., 2017). This conclusion aligns with our findings. We also found that grazing does not affect tall-stature plant height across a wide species range, possibly related to livestock selective herbivory (Zanella et al., 2021). In summary, grazing-prohibited grassland reduces surface aerodynamics primarily through higher densities of tall-stature plants.

Arid region grasses have slender leaves and clumped growth, with each clump functioning as a discretely distributed roughness element. Some wind tunnel experiments have used physical models such as cylinders, cones, and inverted truncated cones to simulate roughness elements (Liu et al., 2021). While such methods reduce experimental workload and yield conclusions similar to field tests, they neglect interspecific leaf dissimilarities—a primary difference caused by grazing measures (Yan et al., 2015). CFD simulation effectively avoids this limitation.

4.2 Influencing Factors of Z_0 and u^*

Wind speed profiling is a common method for monitoring surface wind flow fields, with logarithmic functions providing sufficient fitting conditions for deriving Z_0 and u . *However, monitoring time intervals and heights can affect Z_0 and u calculation accuracy* (Bañuelos-Ruedas et al., 2010). Differences between daily and hourly data can also yield different Z_0 and u^* values (Yu et al., 2018). Wind speed fluctuations across different time scales affect aerodynamic characteristic

expression (Liu et al., 2022). Differences in Z_0 and u^* generated by time scale appear related to changes in aerodynamic resistance of plant leaves caused by wind deformation (Walter et al., 2012).

Our results demonstrate that aerodynamic characteristics are influenced by wind data selection and vegetation characteristics. Therefore, deriving Z_0 and u^* using fitted wind speed profile functions requires knowledge of whether they are affected by vegetation-induced wind flow field changes, which influences functional expressions (Barnéoud and Ek, 2019). CFD results indicated that grazing-prohibited grassland showed greater wind flow field differences with increasing height compared to grazed grassland. Furthermore, deriving an optimal functional relationship between Z_0 and u^* can avoid parameter calculation errors caused by sudden changes in instantaneous wind speed profiles.

5 Conclusions

This study divided transit wind speeds into five intervals to examine effects of different transit wind speeds and vegetation parameters on within-canopy wind speed and analyze Z_0 and u^* relationships with $V_{0.1}$ in grazing-prohibited and grazed grasslands at Eritu pasture. We explored wind speed-vegetation relationships using CFD simulation. Results showed that with increasing transit wind speeds, the Z_0 - $V_{0.1}$ fitting relationship decreased in grazing-prohibited grassland, while it initially increased then decreased in grazed grassland. As Z_0 increased, $V_{0.1}$ exhibited three stages: a sharp change zone, steady change zone, and flat zone, with the sharp change zone disappearing at 8.0-10.0 m/s transit wind speed in grazing-prohibited grassland.

Dividing transit wind speeds into intervals improved the Z_0 - $V_{0.1}$ fitting relationship. In semiarid grasslands with sparse vegetation, tall-stature plant number had a more significant effect on windproof capacity than plant height. By dividing transit wind speeds into intervals, this study advances understanding of wind speed-grassland canopy linkages and provides a theoretical framework for further clarifying aerodynamic effects on grasslands.

Conflict of Interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgements

This research was funded by the National Natural Science Foundation of China (52279017 and 52079063), Technological Achievements of Inner Mongolia Au-

onomous Region of China (2020CG0054 and 2022YFDZ0050), the Graduate Education Innovation Program of Inner Mongolia Autonomous Region of China (B20210188Z), and the Program for Innovative Research Team in Universities of Inner Mongolia Autonomous Region, China (NMGIRT2313). The authors thank editors and anonymous reviewers for constructive comments that improved this manuscript.

Author Contributions

Conceptualization: LI Ruishen, ZHANG Shengwei; Data curation: LIN Xi; Methodology: LI Ruishen; Investigation: WANG Shuai; Formal analysis: LIN Xi; Writing—original draft: LI Ruishen; Writing—review and editing: LI Ruishen; Funding acquisition: ZHANG Shengwei; Resources: LI Fengming; Supervision: ZHANG Shengwei; Project administration: YANG Lin; Software: YANG Lin; Validation: LI Fengming; Visualization: WANG Shuai.

Open Access

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third-party material in this article are included under the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alberton B, Torres R d S, Cancian L F, et al. 2017. Introducing digital cameras to monitor plant phenology in the tropics: applications for conservation. *Perspectives in Ecology and Conservation*, 15(2): 82-90.
- Bañuelos-Ruedas F, Angeles-Camacho C, Rios-Marcuello S. 2010. Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights. *Renewable and Sustainable Energy Reviews*, 14(8): 2383-2391.
- Barnéoud P, Ek N. 2019. On the application of linear regression to surface-layer wind profiles for deducing roughness length and friction velocity. *Boundary-Layer Meteorology*, 174(2): 327-339.

- de Souza C M, Dias-Júnior C Q, Tóta J, et al. 2016. An empirical-analytical model of the vertical wind speed profile above and within an Amazon forest site. *Meteorological Applications*, 23(1): 158-164.
- Dong Z B, Gao S Y, Fryrear D W. 2001. Drag coefficients, roughness length and zero-plane displacement height as disturbed by artificial standing vegetation. *Journal of Arid Environments*, 49(3): 485-505.
- Du H Q, Wang T, Xue X. 2017. Field determination for roughness length above the different non-erodible surfaces. *Sciences in Cold and Arid Regions*, 9(1): 67-77.
- Fu L T, Fan Q, Huang Z L. 2019. Wind speed acceleration around a single low solid roughness in atmospheric boundary layer. *Scientific Reports*, 9(1): 12002, doi: 10.1038/s41598-019-48574-7.
- Gonzales H B, Ravi S, Li J R, et al. 2018. Ecohydrological implications of aeolian sediment trapping by sparse vegetation in drylands. *Ecohydrology*, 11(7): e1986, doi: 10.1002/eco.1986.
- Haghighi E, Or D. 2015. Interactions of bluff-body obstacles with turbulent airflows affecting evaporative fluxes from porous surfaces. *Journal of Hydrology*, 530: 103-116.
- Jäschke Y, Heberling G, Wesche K. 2020. Environmental controls override grazing effects on plant functional traits in Tibetan rangelands. *Functional Ecology*, 34(3): 747-760.
- Kang L Q, Zhang J J, Zou X Y, et al. 2019. Experimental investigation of the aerodynamic roughness length for flexible plants. *Boundary-Layer Meteorology*, 172(3): 397-416.
- Kinugasa T, Sagayama T, Gantsetseg B, et al. 2021. Effect of simulated grazing on sediment trapping by single plants: A wind-tunnel experiment with two grassland species in Mongolia. *CATENA*, 202: 105262, doi: 10.1016/j.catena.2021.105262.
- Levin N, Ben-Dor E, Kidron G J, et al. 2008. Estimation of surface roughness (z_0) over a stabilizing coastal dune field based on vegetation and topography. *Earth Surface Processes and Landforms*, 33(10): 1520-1541.
- Li X, Feng G, Sharratt B, et al. 2015. Aerodynamic properties of agricultural and natural surfaces in northwestern Tarim Basin. *Agricultural and Forest Meteorology*, 204: 37-45.
- Liu J Q, Kimura R, Miyawaki M, et al. 2021. Effects of plants with different shapes and coverage on the blown-sand flux and roughness length examined by wind tunnel experiments. *CATENA*, 197: 104976, doi: 10.1016/j.catena.2020.104976.
- Liu X Y, Zhang C L, Zhang H, et al. 2022. Characteristics of wind velocity pulsation and its relation to average wind velocity and friction wind velocity.

Bulletin of Soil and Water Conservation, 40(5): 60-63, 78. (in Chinese)

Luo Q, Zhen L, Xiao Y, et al. 2020. The effects of different types of vegetation restoration on wind erosion prevention: A case study in Yanchi. *Environmental Research Letters*, 15(11): 115001, doi: 10.1088/1748-9326/abbaff.

Miri A, Dragovich D, Dong Z B. 2017. Vegetation morphologic and aerodynamic characteristics reduce aeolian erosion. *Scientific Reports*, 7: 12831, doi: 10.1038/s41598-017-13084-x.

Onoda Y, Westoby M, Adler P B, et al. 2011. Global patterns of leaf mechanical properties. *Ecology Letters*, 14(3): 301-312.

Pi H, Huggins D R, Sharratt B. 2020. Threshold friction velocities influenced by standing crop residue in the inland Pacific Northwest, USA. *Land Degradation and Development*, 31(16): 2356-2368.

Rauber L R, Sequinatto L, Kaiser D R, et al. 2021. Soil physical properties in a natural highland grassland in southern Brazil subjected to a range of grazing heights. *Agriculture, Ecosystems and Environment*, 319: 107515, doi: 10.1016/j.agee.2021.107515.

Stanhill G. 1969. A simple instrument for the field measurement of turbulent diffusion flux. *Journal of Applied Meteorology and Climatology*, 8(4): 509-513.

Stull R B. 1988. *An Introduction to Boundary Layer Meteorology*. New York: Springer Science and Business Media.

Török P, Penksza K, Tóth E, et al. 2018. Vegetation type and grazing intensity jointly shape grazing effects on grassland biodiversity. *Ecology and Evolution*, 8(20): 10326-10335.

Walter B, Gromke C, Leonard K C, et al. 2012. Spatio-temporal surface shear-stress variability in live plant canopies and cube arrays. *Boundary-Layer Meteorology*, 143(2): 337-356.

Xin G W, Huang N, Zhang J, et al. 2021. Investigations into the design of sand control fence for Gobi buildings. *Aeolian Research*, 49: 100662, doi: 10.1016/j.aeolia.2020.100662.

Xiong P F, Chen Z F, Zhou J J, et al. 2021. Aboveground biomass production and dominant species type determined canopy storage capacity of abandoned grassland communities on semiarid Loess Plateau. *Ecohydrology*, 14(2): e2265, doi: 10.1002/eco.2265.

Yan R R, Xin X P, Yan Y C, et al. 2015. Impacts of differing grazing rates on canopy structure and species composition in Hulunber meadow steppe. *Range-land Ecology and Management*, 68(1): 54-64.

Yu M Z, Wu B F, Zeng H W, et al. 2018. The impacts of vegetation and meteorological factors on aerodynamic roughness length at different time scales. *Atmosphere*, 9(4): 149, doi: 10.3390/atmos9040149.

Zanella P G, Junior L H P D G, Pinto C E, et al. 2021. Grazing intensity drives plant diversity but does not affect forage production in a natural grassland dominated by the tussock-forming grass *Andropogon lateralis* Nees. *Scientific Reports*, 11(1): 16744, doi: 10.1038/s41598-021-96208-8.

Zhang Q, Zeng J, Yao T. 2012. Interaction of aerodynamic roughness length and windflow conditions and its parameterization over vegetation surface. *Chinese Science Bulletin*, 57(13): 1559-1567.

Zhang W, Wu J J, Jiang A. 2022. Numerical study on aerodynamic roughness of forest. *Earth Science Informatics*, 15(1): 1-12.

Zheng M M, Song J, Ru J Y, et al. 2020. Effects of grazing, wind erosion, and dust deposition on plant community composition and structure in a temperate steppe. *Ecosystems*, 24(2): 403-420.

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

Source: ChinaXiv –Machine translation. Verify with original.