Research Progress on Aerodynamic Roughness (Postprint)

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Abstract

Aerodynamic roughness is an important parameter for characterizing momentum and energy exchange between the Earth' s surface and the atmosphere, which is crucial for investigating various land surface processes and climate change. Remote sensing technology, as a long-distance monitoring approach, offers advantages of high timeliness and cost-effectiveness in aerodynamic roughness studies, enabling dynamic monitoring at regional or large spatial scales. Therefore, estimating aerodynamic roughness using remote sensing technology has emerged as a research hotspot. This paper systematically reviews recent domestic and international research progress on aerodynamic roughness, focusing on methods for estimating aerodynamic roughness over vegetated underlying surfaces using remote sensing technology. The strengths and weaknesses of various estimation methods are summarized, the impacts of meteorological factors and morphological characteristics of surface roughness elements on aerodynamic roughness are analyzed, and prospects for the application of remote sensing technology in this field are presented, aiming to provide insights for research on remote sensing monitoring of aerodynamic roughness.

Full Text

Research Progress on Aerodynamic Roughness

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Abstract

Aerodynamic roughness is a critical parameter that measures the exchange of momentum and energy between the Earth' s surface and the atmosphere, playing a vital role in investigating various surface processes and climate change.

Remote sensing technology, as a long-range monitoring approach, offers significant advantages in studying aerodynamic roughness due to its high timeliness and cost-effectiveness, enabling dynamic monitoring at regional or larger spatial scales. Consequently, estimating aerodynamic roughness using remote sensing technology has become a prominent research topic. This paper systematically reviews recent advances in aerodynamic roughness research both domestically and internationally, focusing on methods for estimating aerodynamic roughness over vegetated surfaces using remote sensing. We summarize the strengths and limitations of various estimation approaches and analyze the influences of meteorological factors and morphological characteristics of surface roughness elements on aerodynamic roughness. Furthermore, we discuss future prospects for remote sensing applications in this field, aiming to provide insights for subsequent research on remote sensing monitoring of aerodynamic roughness.

Keywords: aerodynamic roughness; remote sensing; research status; influencing factors

1 Methods Based on Measured Data

Currently, with the deepening of research on surface aerodynamics by scholars worldwide, estimating aerodynamic roughness over non-uniform surfaces at regional scales has become a hot topic. Methods based on measured data are prerequisites for validating the accuracy of remote sensing approaches and primarily include the canopy height fixed ratio method, wind tunnel experiments, and field experiments. The subsequently developed look-up table method enables estimation of aerodynamic roughness over larger areas by assigning constant values based on land use types, though this approach ignores the inherent spatiotemporal variations of specific land use types.

1.1 Canopy Height Fixed Ratio Method

Using vegetation average height to estimate aerodynamic roughness is one of the most common methods. For vegetated surfaces, vegetation height is a key factor influencing surface roughness conditions and drag force magnitude. In related studies, simple empirical rules have been applied to relate vegetation height to aerodynamic roughness. For instance, some researchers parameterized the aerodynamic roughness of northern forest canopies with complex geometric and spatial structures using vegetation height (H) to simplify the representation of aerodynamic roughness (z_0), with the calculation formula:

$$z_0 = 0.125H$$

Masseroni et al. measured the zero-plane displacement height and aerodynamic roughness of rice fields throughout the agricultural season and found that both parameters correlated well with H during the entire growing season ($R^2 > 0.9$). Santos et al. studied evapotranspiration in olive orchards using a satellite-based energy balance model (METRIC), where the aerodynamic roughness function was:

$$z_0 = 0.068H$$

This method establishes a simple empirical relationship with a single variable correlated to vegetation average height.

1.2 Field Experiment Method

When obtaining measured meteorological data in the field, three main methods have been developed: wind profile method, eddy covariance (EC) method, and large aperture scintillometer (LAS) method. The calculation approaches using field measured data include least squares fitting iteration, Newton iteration, and temperature variance method.

1.2.1 Wind Profile Method Monitoring equipment commonly used in meteorological stations includes wind speed sensors, wind direction sensors, and temperature-humidity sensors, which store corresponding meteorological element values in data collectors. When calculating aerodynamic roughness using meteorological observation data, the Monin-Obukhov similarity theory is applied. Based on wind speed profile and temperature profile data measured at different heights at the same time, the optimal solution for aerodynamic roughness is obtained through least squares fitting iteration according to micrometeorological principles and a series of calculation formulas. Under neutral atmospheric stability conditions, the calculation formula is:

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z-d}{z_0}\right)$$

where u is wind speed (m s^{-1}), u_* is friction velocity (m s^{-1}), k is the Von Karman constant (value 0.4), z_0 is aerodynamic roughness (m), d is zero-plane displacement (m), and z is reference height (m). The results are analyzed using least squares regression to determine the best fitting relationship for solving z_0.

1.2.2 Eddy Covariance (EC) Method and Large Aperture Scintillometer (LAS) Method The EC observation system is a micrometeorological measurement method that uses the eddy covariance principle and fast-response sensors to measure material and energy exchange between the atmosphere and underlying surface. It is currently the most accurate and commonly used instrument for surface flux observation. The LAS system consists of a transmitter and receiver. The receiver captures the transmitted beam affected by atmospheric fluctuations along the optical path and expresses atmospheric turbulence intensity using the structure parameter of the refractive index to calculate turbulent flux. Compared with EC, LAS can measure large-area turbulent fluxes due to optical paths ranging from hundreds to thousands of meters, making it more suitable for calculating aerodynamic roughness over non-uniform underlying surfaces at large spatial scales. Additionally, when calculating fluxes, LAS data include variables such as wind speed, atmospheric stability, and friction velocity for calculating aerodynamic roughness, whereas wind speed data must be obtained from meteorological station observations.

1.3 Wind Tunnel Method

Wind tunnel experiments simulate natural wind effects on soil erosion under different vegetation cover densities and shapes in the laboratory. Wind speed at different heights is obtained, and aerodynamic roughness is calculated using formulas under neutral atmospheric stability conditions. The wind tunnel consists of a transition section, rectification section, contraction section, and test section, with a supporting wind speed test control system. The test section simulates natural wind and can generate free vortex airflow and stable flow fields. Wind tunnel experiments set important parameters such as model crop height, porosity, and row spacing to simulate the wind-blocking effect of surface vegetation under different roughness conditions. Compared with the canopy height fixed ratio method, this approach is more accurate for studying aerodynamic roughness.

Vegetation, as one of the main factors affecting wind erosion, has been studied extensively through wind tunnel simulation experiments to investigate the influence of vegetation surface roughness on soil wind erosion. Mobile wind erosion tunnels have solved the problem of disturbing the original surface soil during sampling in traditional wind tunnel experiments.

1.4 Method Review

The canopy height fixed ratio method employs a simplified empirical relationship with a single variable, but related studies show that meteorological factors and terrain undulation affect aerodynamic roughness over vegetated surfaces. Field experiment methods have strict data quality requirements and are generally used as ground truth values for validation, though minor influences from natural conditions and instrument systems can cause significant calculation errors, and results only represent a certain source area range, limiting application to larger spatial scales. Wind tunnel methods consider the combined effects of airflow and surface roughness elements, simulating wind erosion under different wind speeds and surface cover conditions in ideal states. However, the disadvantage lies in adopting fluid similarity principles that differ from real surface conditions, with studies finding low similarity between wind tunnel and field measured wind-sand results, and the required equipment is costly and time-consuming.

2 Remote Sensing Methods

Remote sensing images have large coverage, short observation cycles, and multiple acquisition pathways, providing outstanding scientific and technical advantages for studying aerodynamic roughness at large spatial scales. Remote sensing methods calculate aerodynamic roughness by inverting surface or atmospheric parameters input into models.

2.1 Vegetation Index Model Method

Aerodynamic roughness is related to surface characteristics of roughness elements. Compared with water bodies and bare land, vegetation has complex morphological features and obvious dynamic changes, making it necessary to introduce vegetation indices for estimating aerodynamic roughness in remote sensing. Vegetation indices measure surface vegetation conditions based on spectral characteristics and multi-band combinations. Optical satellite data inversion methods generally establish relationship models between vegetation indices and aerodynamic roughness or zero-plane displacement height, then convert to aerodynamic roughness through empirical models.

2.1.1 Normalized Difference Vegetation Index (NDVI) NDVI is the best indicator of vegetation growth status and spatial distribution density. It is calculated from near-infrared band reflectance (ρ_{nir}) and red band reflectance (ρ_{red}) as:

$$\mathrm{NDVI} = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}}$$

When using remote sensing technology to study aerodynamic roughness over vegetated surfaces, NDVI has been widely applied. For example, some researchers used Landsat TM NDVI to establish empirical relationships with aerodynamic roughness estimated from turbulent flux observations at Heihe River Basin experimental sites. Gupta et al. used NOAA AVHRR NDVI combined with surface process parameters to establish relationships for semi-arid regions in India. Abbas et al. developed optimal mathematical models describing the NDVI-aerodynamic roughness relationship to map roughness length across Iraq.

2.1.2 Leaf Area Index (LAI) LAI quantifies green leaf area per unit ground area and is a fundamental attribute of vegetation canopy structure and function. Numerous studies show that aerodynamic roughness relates to vegetation canopy structure parameters, making LAI more strongly correlated than NDVI in some cases. Zero-plane displacement height and aerodynamic roughness are strong functions of LAI. Some researchers have used remote sensing to invert LAI and wind speed for estimating aerodynamic roughness in sparse vegetation areas. Others have expressed the ratio of aerodynamic roughness to canopy height to characterize canopy structure complexity and examine relationships with albedo.

2.1.3 Frontal Area Index (FAI) FAI is defined as the ratio of frontal area to unit ground area, later expressed as canopy area index (Λ) representing the total single-sided area of all canopy elements per unit ground area. Λ includes all momentum-absorbing canopy elements. Some researchers have established parameterization methods for natural or randomly distributed plants using Λ and applied them to estimate local aerodynamic roughness from satellite images.

2.1.4 Bidirectional Reflectance Distribution Function Index Vegetation indices calculated from single observation angles have limited capability for retrieving three-dimensional vegetation structure closely related to aerodynamic roughness. A potential solution is introducing multi-angle optical remote sensing. The semi-empirical BRDF model represents bidirectional reflectance as a linear weighted sum of three kernels:

$$\rho(\theta_i, \theta_v, \phi) = f_{iso} + f_{vol} K_{vol}(\theta_i, \theta_v, \phi) + f_{geo} K_{geo}(\theta_i, \theta_v, \phi)$$

where ρ is bidirectional reflectance, θ_i is solar zenith angle, θ_v is view zenith angle, ϕ is relative azimuth angle, K_{vol} and K_{geo} are volume scattering and geometric optical scattering kernels, and f_{iso}, f_{vol}, f_{geo} are kernel coefficients. Based on this, the near-infrared BRDF index (BRDF_R) reflecting surface geometric roughness is calculated. Some studies have combined NDVI and BRDF_R to develop a composite index (HDVI) that shows a power function relationship with grassland aerodynamic roughness during the growing season.

2.2 LiDAR Method

Aerodynamic roughness is affected by the height, geometric shape, and density of surface roughness elements, including vegetation and micro- to macro-scale topographic features. LiDAR shows great potential in characterizing surface and roughness element features, offering technical advantages over optical satellites. Airborne LiDAR is an active measurement method using laser detection and ranging to obtain three-dimensional structures of land surfaces and vegetation from point cloud data, providing new methods for estimating aerodynamic roughness. Some researchers have used calibrated radar backscatter coefficients to establish relationships with aerodynamic roughness, finding good correlations for various underlying surfaces. Others have obtained digital elevation models (DEM) and digital surface models (DSM) from LiDAR point cloud data to estimate aerodynamic roughness. UAV-borne LiDAR has been used to acquire three-dimensional vegetation structure data for assessing model accuracy in estimating aerodynamic roughness over farmland and evergreen trees.

2.3 Multi-Source Data Combination Method

Different influencing factors dominate aerodynamic roughness in different study areas, and various remote sensing data sources have distinct characteristics and advantages. Combining multi-source remote sensing data to establish aerodynamic models demonstrates clear advantages. Some researchers have proposed using albedo (α) to help distinguish vegetation classes with similar NDVI but different heights, establishing relationships with aerodynamic roughness. Others have comprehensively considered vegetation information, terrain factors, and geometric roughness of non-vegetated surfaces to estimate aerodynamic roughness, where vegetation roughness is expressed as a function of NDVI, terrain roughness considers slope effects, and surface geometric roughness from radar imagery represents non-vegetated areas. The regional comprehensive effective roughness is a weighted function of these three factors. Multi-source remote sensing synergy methods comprehensively consider influencing factors of aerodynamic roughness, overcoming limitations of single data sources through heterogeneous observation data combination to achieve mutual complementarity. However, challenges remain in coupling multiple factors and matching spatiotemporal resolutions.

3 Influencing Factors of Aerodynamic Roughness

The magnitude of aerodynamic roughness primarily depends on the geometric characteristics and distribution density of surface roughness elements, while also being influenced by atmospheric factors such as wind speed, wind direction, and atmospheric stability. In wind erosion models, vegetation physical structure interacts with wind through drag force, making aerodynamic roughness a dynamic parameter resulting from comprehensive factor interactions.

3.1 Meteorological Factors

3.1.1 Wind Speed Under certain surface conditions, aerodynamic roughness is not constant but varies significantly with wind speed. For vegetated surfaces, increasing wind speed changes vegetation geometry, causing plants to tilt in the same direction under wind action, thereby decreasing aerodynamic roughness until reaching a critical point where it stabilizes. Studies have found that aerodynamic roughness shows an exponential relationship with wind speed under different vegetation densities. For grassland and forest mountain surfaces, wind speed is a primary influencing factor, while for flat farmland it is secondary. Aerodynamic roughness shows the greatest variation at low wind speeds and less variation at higher wind speeds.

3.1.2 Friction Wind Speed Friction wind speed measures wind speed gradients resulting from ground friction and reflects airflow shear stress on the surface. Research shows that friction wind speed has a linear relationship with average wind speed. Aerodynamic roughness increases with friction wind speed, but when wind speed increases to the point of vegetation lodging, boundary layer shear stress increases, causing the growth rate of aerodynamic roughness and friction wind speed to decrease or even become negative.

3.1.3 Wind Direction Wind direction effects on aerodynamic roughness depend on terrain heterogeneity. In complex terrain, each wind direction presents different roughness element densities and distributions. For uniform, flat surfaces, aerodynamic roughness changes little with wind direction due to minimal differences in roughness elements across wind directions. However, for non-uniform surfaces, different wind directions create different turbulent drag forces, resulting in varying aerodynamic roughness values. Aerodynamic roughness variation with wind direction is formed by the combined action of surface roughness elements and airflow in the wind fetch area, making it difficult to obtain aerodynamic roughness for non-uniform surfaces through observation alone.

3.1.4 Atmospheric Stability Aerodynamic roughness relates to near-surface atmospheric stratification, typically measured by stability. Different atmospheric stability conditions affect turbulence generation. Previous studies assumed neutral atmospheric conditions, but this ideal state is difficult to achieve in practice. Aerodynamic roughness differs significantly under different stability conditions, being larger under stable conditions than unstable conditions. Atmospheric stability is closely related to diurnal cycles: during daytime, unstable atmospheric conditions due to solar radiation and turbulent exchange between vegetation and atmosphere keep aerodynamic roughness at low levels; at night, weakened turbulence and more stable conditions cause aerodynamic roughness to increase significantly.

3.2 Morphological Characteristics of Surface Roughness Elements

Surface roughness elements (such as vegetation and other obstacles) structure and spatial distribution affect aerodynamic roughness. Vegetation morphological characteristics including height, density, and coverage influence surface roughness conditions and drag force magnitude. Studies show that aerodynamic roughness relates to atmospheric stability but is more sensitive to surface roughness element changes. Vegetation height, density, and coverage reflect vegetation distribution, density, and photosynthetic area size. Vegetation density strongly affects aerodynamic roughness—among vegetation of the same height but different densities, sparser vegetation has smaller aerodynamic roughness. Research indicates that increasing vegetation coverage can enhance surface aerodynamic roughness due to flow field diversion around vegetation. During the vegetation growth period, LAI initially increases aerodynamic roughness, reaching a peak before decreasing because overly dense vegetation prevents wind from penetrating the canopy, reducing surface roughness.

4 Outlook

Remote sensing technology has laid the foundation for aerodynamic roughness parameterization over large-scale areas, opening multiple research avenues. As remote sensing observation systems continue to innovate in temporal, spatial, and spectral resolution, better application to aerodynamic roughness requires comprehensive consideration of surface aerodynamic characteristics. Multi-angle observations can capture non-uniform scattering of solar light by vegetation, giving multi-angle remote sensing data unparalleled advantages in describing crop canopy structure. Therefore, as remote sensing technology develops toward multi-angle observation and high spatiotemporal resolution, the accuracy of remotely sensed aerodynamic roughness datasets will improve.

Remote sensing methods demonstrate unique advantages in aerodynamic roughness research, but uncertainties arise when using remote sensing spatial analysis methods to estimate aerodynamic roughness over vegetated surfaces at macro scales, primarily because surface undulation, vegetation changes, and dynamic land-atmosphere energy balance are not fully considered. Research shows that surface undulation affects roughness element distribution and surface flux changes, influencing surface roughness. Therefore, aerodynamic roughness research should comprehensively consider meteorological factors, roughness element morphological factors, and terrain factors to analyze main driving factors and extract effective feature information from multi-dimensional data. Future work should fully leverage the advantages of multiple data source integration to develop more refined long-term aerodynamic roughness change datasets, integrating remote sensing, station observations, and surface turbulence models to analyze aerodynamic roughness variations across spatiotemporal scales. For complex underlying surfaces, attention should be paid to validation and calibration using measured data, combining remote sensing inversion with ground observations to ensure model accuracy. Currently, estimation and analysis of aerodynamic roughness mainly focus on vegetated surfaces, and future research could expand to other underlying surface types such as urban areas.

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