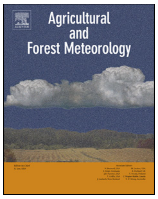
Agricultural and Forest Meteorology 263 (2018) 362–372

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Wind tunnel study of airflow recovery on the lee side of single plants

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ARTICLE INFO

Keywords:
Single plant
Airflow recovery
Turbulence intensity
Wind tunnel
Shear velocity

ABSTRACT

Plants play an important role on reducing the soil erosion rate and preventing blown sand motion. The primary cause is the airflow change around the plant, especially for the lee side of plants. Although scientist have researched this topic, significant problems remain concerning airflow around plants. Therefore, we conducted a series of wind tunnel experiments to simulate average airflow speed and turbulence intensities on the lee side of eight single plants with varying characteristics under different shear velocities by utilizing a hot film anemometer. We come to the following conclusions:

(1) Variation in the airflow speed along the plant downwind direction is related to the porosity and the height-to-width ratio (H/W). The weakened degree of wind speed decreases with plant porosity, and the minimum wind speeds ($u_{\min}$) at different heights are different for different H/W. For large H/W (H/W ≥ 2), the values of $u_{\min}$ appear at the location of 1 H in the lee side of the plant, while the location where $u_{\min}$ occurs for small H/W (H/W ≤ 0.5) is related to the height. The location most frequently occurs between 3 h and 5 h.

(2) This paper presented a modification for relaxation equation to express airflow recovery on the lee side of plant and developed the relationships of the minimal wind speed ($u_{\min}$), occurring lee-side location (x_0), and the characteristic length (l) in this modified relation equation, with different plant characteristic. The value of $u_{\min}$ increases with the plant porosity (β) in a linear function of $u_{\min} = 0.0183\beta\text{-}0.65$ and the location (x_0) where $u_{\min}$ occurs and the characteristic length for wind speed recovery are proportional to the reciprocal of the ratio of plant height-to-width. Their relationships can be expressed as $x_0 = 1.68(\mathrm{H/W})^{-1}$ and $l = 5.30(\mathrm{H/W})^{-1}$, respectively.

(3) The turbulence intensity downwind direction of the plant is several times the intensity of the incoming flow, and the peak turbulence intensity can reach up to 50%. The more significantly the wind speed weakens, the more significant the increase in the turbulence intensity. The standard deviation of the wind speed varies slightly.

1. Introduction

Plants can effectively stabilize and block aeolian sediment transport and change aeolian landforms, as well as reduce the soil erosion rate by directly covering part of the land surface, capturing particles in sand streams and lowering wind speed on the lee side of plants, especially in the downwind area (Hesp, 1981; Ash and Wasson, 1983; Buckley, 1987; Van de Ven et al., 1989; Wolfe and Nickling, 1993; Wiggs et al., 1995; Ling et al., 2003; Hesse and Simpson, 2006; Gillies et al., 2014). Thus, it is meaningful to study the airflow field on the lee side of plants to gain a better understanding of the soil erosion rate over plant-covered land surfaces. In order to elucidate the influence range and intensity of the plant on airflow and sediment transport, it is very necessary to determine the minimum wind speed and its location and the initial position of the re-equilibration zone by clarifying the airflow recovery law of the wind direction at the position of the minimum wind speed on the lee side of plants (Cleugh,1998; Okin, 2008; Mayaud et al., 2017a,b). Hence, the minimum wind speed and its location play key roles in demonstrating how plants can be utilized to reduce soil erosion, as well as to prevent and control wind-sand hazards.

In general, most scholars divided airflow fields based on the airflow speed variation: weak deceleration zone in the upwind direction of a single plant (Wu et al., 2015), acceleration zone on both sides of the plant (Ash and Wasson, 1983; Leenders et al., 2011), and wake

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https://doi.org/10.1016/j.agrformet.2018.08.025
Received 20 November 2017; Received in revised form 18 August 2018; Accepted 25 August 2018

deceleration zone in the downwind direction of the plant (Ash and Wasson, 1983; Leenders et al., 2007; Mayaud et al., 2017a,b). Of these zones, the wake deceleration zone on the lee side of the plant has been the long-term focus of scientists (Ash and Wasson, 1983; Sterk et al., 1998; Van Boxel et al., 2004; Gillies et al., 2007; Leenders et al., 2007, 2011; Weaver and Wiggs, 2011). The wind speed variation downwind of the plant (positive axis) is more significant than the wind speed variation along the plant. The airflow variation along the positive downwind axis is, therefore, usually used to represent the overall airflow variation in the wake deceleration zone of a single plant (Leenders et al., 2007; Wu et al., 2015; Mayaud et al., 2017a,b).

Generally, after the airflow in the downwind direction of the plant reaches its minimum wind speed, the airflow gradually recovers to arrive at the upwind incoming speed. This process in existing literature can be generally expressed as a complex polynomial equation as (Hagen, 1996; Leenders et al., 2011):

$$u = u_r(1 - e^{-ax^2} + be^{(-0.003(x+c)^d)}) \tag{1}$$

Where u_r is the upwind incoming speed (m/s), x is a location lee side of the plant, u is the airflow velocity at the location x, and parameters a, b, c and d are the fitted coefficients (Hagen, 1996; Leenders et al., 2011). Okin (2008) and Mayaud et al., (2017a,b) presented another expression to model this process,

$$u = (u_r - u_{min})(1 - e^{-\alpha x}) + u_{min} \tag{2}$$

Where $u_{\min}$ is the minimum wind velocity on lee side of the plant and α is a fitted coefficient (Okin, 2008; Mayaud et al., 2017a,b).

If we assume another parameter as $1/\alpha$, Eq. (2) has a more definitive physical meaning as it is in the form of the relaxation function. Even such a modification, it has two shortcomings:

First, it indicates that the location where $u_{\min}$ appears in the wake deceleration zone corresponds to the plant location. In contrast, a number of observational studies have shown that $u_{\min}$ might appear at a location several times that of the plant height in its downwind direction (Leenders et al., 2007, 2011; Wu et al., 2015; Mayaud et al., 2017a,b). In turn, non-uniform vertical and horizontal distributions of plant leaves and branches can result in significant differences in the inferred location where $u_{\min}$ occurs and also in the airflow variation at different heights. Second, Mayaud et al., (2017a,b) provided quantitative relationships of the parameters $u_{\min}$ and α with porosity, but they ignored important parameters such as the shape, height, and width of the plant, and its vertical variation (Okin, 2008). Thus, although encouraging research results have been achieved; further studies are urgently needed to address the recovery process of airflow and its relative parameters in studying airflow variations in the direction downwind of the plant.

The methods for studying airflow variation in the lee side of plant include computational fluid dynamics (CFD) simulation (Wilson, 1988; Gross, 1987; Zeng and Takahashi, 2000; Wang et al.,2001; Yue et al., 2007), field observation (King et al., 2006; Gillies et al., 2007), and wind tunnel experiments (Suter-Burri et al., 2013). The CFD simulation can avoid accidental errors associated with field observation and wind tunnel experiments (Rosenfeld et al., 2010), CFD simulation results need to be verified by experimental data (Dupont et al., 2014). Field observation is a traditional method to study airflow on the lee side of plants using cup anemometers and ultrasonic anemometers to measure airflows on the lee side of single plants (Leenders et al., 2007), Shrubs (Gillies et al., 2014) or forest shelter belts (Cleugh,1998; Torita and Satou, 2007). Previous studies mainly focused on the airflow distribution along the axis from the upwind to downwind direction. Due to the complexity and variability of the field conditions, especially for the fluctuation along the wind direction which result in deviation of the observational location from the positive downwind direction of the plant, field observations cannot truly represent the airflow speed variation on the lee side of the. In addition, as plants are three-dimensional, porous, irregular media with certain flexibilities, the plant shape and the regularity, porosity and flexibility of its branches and leaves influence airflow on the lee side of a single plant. Therefore, difficulties exist in independently identifying the effects of each factor on the airflow distribution using field observations. Wind tunnel experiments can be conducted under controlled conditions and are therefore convenient for statistical studies. Wind tunnel experiments usually use Pitot tubes (Wu et al., 2015), hot wires or film anemometers (Liu et al., 2018), and particle image velocimetry (PIV) (Dong et al., 2010; Lee and Lee, 2012) to study airflow fields on the lee side of single plants (Dong et al., 2008; Lee et al., 2014), and nebkhas and forest shelter belts (Dong et al., 2010). Many studies have been conducted in forests, and in comparison, studies focusing on single plants have been quite limited. Moreover, similarities in the geometry, dynamics, and movements among wind tunnel experiments cause the boundary layer thickness of the wind tunnel and the simulation height of the plant to be much smaller than those observed in the field. Thus, it is important for a wind tunnel simulation to comparably match the corresponding field observation.

In this experiment, a hot film anemometer is used to measure average airflow speed and turbulence intensities on the lee side of eight single plants with varying characteristics in a wind tunnel. Airflow speeds were compared at different distances with different heights by developing a new model for airflow recovery along the plant downwind direction and relative quantitative relationships between parameters in the recovery model and plant characteristics. This allowed for an examination of large spatial variabilities of airflow speeds on the lee side of single plants and furthermore different recovery distances for different characteristics. This information will help gain a better understanding of the distribution of airflow fields on the lee side of single plants, and reveal the underlying mechanism for the capability of plants to reduce soil erosion.

2. Material and method

2.1. Experimental material

The wind tunnel experiment in this study used plastic plant models; their branches are made of plastic wrapped around thin wires, and their leaves are also made of plastic. The plants have certain flexibilities and are similar to real plants. We studied eight plants of different shapes (Fig. 1) and their characteristic parameters are listed in Table 1. The porosity is an important parameter to represent plant characteristics (Cornelis and Gabriels, 2005; Dong et al., 2007) and is usually measured using photographs (Kenney, 1987). We placed a Nikon D10 digital camera with the pixels of 24.26 million at the location of 1 m in front of each plant for horizontal shooting. The background was a white foam board, which was used to enhance the contrast, and thus, to reduce the perspective effect that can cause picture distortion. The focal distance was set at 85 mm. These photographs were processed using DPVC, a software for vegetation coverage measurement developed by Beijing Normal University. There are six steps as following: 1) cropping the photo so that the plants fill the entire photo; 2) The color photographs are converted into grayscale; 3) The DPVC software automatically identifies the area where the plant is located; 4) We adjust possible errors from DPVC; 5) The coverage degree (α %) is calculated, which is equal to the percentage of the area covered by the plant; and 6) The porosity (β %), equal to 1-α, is calculated. Because the plant shapes are not perfect columns or cubes and their silhouette shapes are not rectangles, there were white areas of different sizes in the pictures (Fig. 2). Thus, the overall porosity of each plant differs from its porosity in the canopy interior with the former reflecting the overall characteristics of the plant porosity and the latter reflecting the local characteristics of the porosity. In this study, we determined the overall porosity (β), canopy porosity (β_c), and local porosity (β_l) at different heights of each plant (Fig. 2). The overall porosity, canopy porosity and local porosity are determined by the area enclosed by the black dashed line, a red dotted line and the yellow virtual color with a height of 0.1 h,