Assessing the vegetation canopy influences on wind flow using wind tunnel experiments with artificial plants

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Wind erosion causes serious problems and considerable threat in most regions of the world. Vegetation on the ground has an important role in controlling wind erosion by covering soil surface and absorbing wind momentum. A set of wind tunnel experiments was performed to quantitatively examine the effect of canopy structure on wind movement. Artificial plastic vegetations with different porosity and canopy shape were introduced as the model canopy. Normalized roughness length (Z_0/H) and shear velocity ratio (R) were analyzed as a function of roughness density (λ). Experiments showed that Z_0/H increases and R decreases as λ reaches a maximum value, $\lambda_{\max}$, while the values of Z_0/H and R showed little change with λ value beyond as $\lambda_{\max}$.

1. Introduction

Wind erosion is the Aeolian process by which soil particles are detached from erodible surface and transported by wind force. It causes serious environment problems and poses considerable threat, especially in arid and semi-arid regions around the world (Stroosnijder 2005). Vegetation protects the ground surface against wind erosion by physically covering a portion of exposed surface and thus absorbing significant fraction of moment flux near the ground (Wolfe and Nickling 1993; Lancaster and Baas 1998; Burri *et al.* 2011). The protective role of vegetation is closely related to ecological parameters, such as plant species, spatial arrangement, canopy porosity and structure (Logie 1982; Buckley 1987; King *et al.* 2005).

The effectiveness of vegetation in reducing wind erosion has been demonstrated in field studies and

wind tunnel experiments. Field measurements have been conducted to examine the role of specific vegetation types in wind erosion control (Wolfe and Nickling 1996) or sand dune development (Gillette and Pitchford 2004). These studies have contributed to understanding the complexity of environmental variables, but the findings were highly site-dependent (Burri *et al.* 2011). As an alternative to field studies, wind tunnel experiments in the laboratory offer problem-oriented solution in the wind erosion study (Burri *et al.* 2011).

Wind tunnel experiments have been conducted either with pieces of dead vegetation (Molina-Aiz *et al.* 2006) or living vegetation (Burri *et al.* 2011), to identify the influence of vegetation on wind movement. Some researchers introduced real vegetation to simulate the extent of wind erosion (Cionco 1972; Buckley 1987; Udo and Takewaka 2007), yet Aeolian process on naturally-vegetated surface

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remains elusive and highly complex (Walter *et al.* 2012), due to heterogeneous and irregular shape of vegetation canopies.

For practical applications, artificial vegetation canopies have been employed in most wind erosion studies. The vegetation model was apparently made of solid cylinders, cubes or hemispheres (Marshall 1971; Wooding *et al.* 1973; Gillette and Stockton 1989; Musick *et al.* 1996; Crawley and Nickling 2003; Brown *et al.* 2008). These rigid and non-porous materials characterized well the aerodynamic shape of vegetation in the experiment by controlling the shape, porosity, and flexibility of canopy structure (Wolfe and Nickling 1993). In some cases, solid roughness elements were reported to describe the actual vegetation canopy poorly and overestimate the aerodynamic roughness of target vegetation (Musick *et al.* 1996; Minvielle *et al.* 2003). Nevertheless, most of the present knowledge on mechanical interaction between airflow and vegetation is driven from the studies with vegetation models, such as wooden sticks (Musick *et al.* 1996; Minvielle *et al.* 2003).

Understanding the aerodynamic phenomena of vegetated surface is significant for coping with the wind-driven soil erosion and taking steps to introduce eco-engineering techniques for reducing its hazard on humanity and environment. However, knowledge on this natural process is still limited and the gap between what is known and what is required is still wide. This especially requires the aerodynamic parameter measurements in vegetation canopies under controlled wind tunnel experiment. The objective of the present study therefore is to experimentally assess the effects of canopy structure on aerodynamic process. Three types of plastic vegetation have been employed as the model canopy. With the experiment, the capability of vegetation to absorb the momentum from wind

was also examined with the concept of shear stress partitioning.

2. Materials and methods

2.1 Wind tunnel experiment

A wind tunnel experiment has been widely used to understand the physical phenomena of wind flow, over and around obstacles under controlled condition. Wind tunnel is designed to artificially produce airflow to explicitly examine the aerodynamic characteristics of flow and the effect of immediate surroundings on airflow. The experiment is usually operated under controlled boundary conditions in order to exclude the uncertainty of experiment parameters, and thus provides with stable and reproducible results.

The present study was performed in the wind tunnel facility at the Rural Development Administration of Korea, illustrated in figure 1. It is an Eiffel-type open-circuit wind tunnel model consisting of diffuser, contraction, and test sections. The experiments were conducted in the 2.0-m wide, 1.7-m high, and 15.0-m long test section. The air-flow velocity is adjustable in a range of 0.3~15 m/s. Readers refer to Lee *et al.* (2004) for more detailed description on the wind tunnel facility used in this study.

Vegetation canopy has complication in geometric morphology according to branch configuration and leaf shape. The canopy also differs slightly in shape and size among the same species. Such complexity and diversity of canopy can make it difficult to understand the aerodynamic interaction with vegetation. In the present study, this challenge was defeated by introducing artificial plastic vegetation model, which accurately mimics actual

Figure 1. Experimental arrangement of wind tunnel test.

vegetation by providing with flexibility, porosity, and relatively uniform configuration.

The experiments were conducted with three different types of artificial plastic vegetation, as shown in figure 2. Canopy model A (Model A) has long, narrow leaves, while Model B and C have round leaves and stalks. Bending modulus was employed in this study to compare the flexibility of artificial plant against actual vegetation. Bending Young's modulus was measured for 10 specimen of each vegetation model with the L&W Bending Resistance Tester SE 016 (Lorentzen & Wettre, Sweden). Model A has approximately 882 MPa of bending Young's modulus. The mean Young's modulus of round-shape leaves was 383 MPa in Model B and 478 MPa in Model C. These values were nearly one-eighth smaller than those of green internodes of grass (Dunn and Dabney 1996). Average 1794 MPa of Young's modulus was estimated in stalks of Model B and C, which is in the range of grass stems (Dunn and Dabney 1996).

Canopy models can be mounted on a 1×2 m wooden board in wind tunnel test section. A total of six configurations were set for each canopy model, placed with either 100, 50, 28, 20, or 14 canopy models on 1×2 m board. Table 1 illustrates the spatial configuration of the canopy model used in the experiments.

A series of experiments were designed to operate with 5 m/s wind velocity and low turbulence (less than 0.5%) in the test section. Automatic traversing system with a multi-channel anemometer Model 1560 (Kanomax Japan Inc., Japan) was positioned in the tunnel to measure wind velocity at the point of interest.

The wind velocity was measured horizontally at two locations: 5 and 100 cm apart from the downwind edge of the canopies. Longitudinal mean

velocities were computed from the measurements taken for 60 sec. The velocity measurements were done at 17 different points from heights of 5–80 cm above the ground at 5 cm intervals. Through the experiments, heights of the inertial sublayer generated by the artificial plastic canopy were recorded to be 25~35, 35~40, and 40~50 cm for Model A, B, and C, respectively. The vertical distribution of wind velocity was also derived using the wind velocity measured at a point of 5 cm away from the downwind edge of the canopy.

2.2 Estimation of aerodynamic characteristics

The protective effect of vegetation is mostly described by an alteration of wind profile or by the theory of stress partitioning. Wind passing through a vegetation canopy induces turbulence, whereby a boundary layer is formed. The vertical distribution of wind velocity can be approximated by a logarithmic profile.

$$u = \frac{u_*}{\kappa} \ln \frac{z - d}{z_0}, \quad (1)$$

where u_* is the shear velocity, κ is the Karman constant (usually taken to be 0.4), z is the measurement

Table 1. Canopy configurations for the experiments.

Configuration type	Number of canopy model	Row space (parallel to wind flow)	Column space (transverse to wind flow)
I	100	10 cm	20 cm
II	50	20 cm	20 cm
III	50	10 cm	40 cm
IV	28	30 cm	30 cm
V	20	30 cm	40 cm
VI	14	30 cm	60 cm

Figure 2. Artificial canopy models for wind tunnel experiment.

height, d is the zero-plane displacement height, and z_0 is the roughness length. The parameters u_* , d , and z_0 are closely associated with the aerodynamic roughness of canopy (Jackson 1981).

The vegetation parameters in equation (1) may be estimated from data on the wind velocity measurements. Zero-plane displacement height was estimated with the mass conservation method (Hagen and Lyles 1988; Dong *et al.* 2001). Roughness length (z_0) expresses the degree of aerodynamic roughness on a wind-flowing surface and denotes the height at which the wind velocity becomes $u = 0$ due to the interaction of plants and other obstacles. This is determined by the amount of turbulence generated by obstacles. The roughness length is widely used for quantitatively identifying the influence of vegetation on wind erosion (Seginer 1974; Minvielle *et al.* 2003). The aerodynamic roughness is quantified by dividing the roughness length by the vegetation height.

Shear stress is the extent of fluid motion in the flow direction induced by its kinematic viscosity. An increase in shear stress causes a proportional increase in the height-dependent change in wind velocity. Shear stress is widely used to estimate the magnitude of vegetation-induced drag force. If there are obstacles such as plants on the ground, the surface roughness increases, and wind energy is absorbed or dissipated by the drag force generated by the obstacles. In other words, the presence of obstacles increases the threshold shear velocity on the ground (Raupach 1992; Wolfe and Nickling 1996).

Shear stress generated by the wind passing over the ground can be expressed as:

$$\tau_0 = \rho u_*^2, \quad (2)$$

where τ_0 is the shear stress at the ground surface, and ρ is the air density. The shear stress occurring on a soil surface without obstacles such as plants can be obtained from the data on the vertical distribution of wind velocity. However, in most cases, the wind-generated shear stress is exerted only on the ground directly, excluding the surface area covered by vegetation. Therefore, wind-generated shear stress can be divided into the shear stress exerted on the vegetation canopy and on the intervening bare surface, as expressed by the following equation (3):

$$\tau_0 = \frac{F_v}{A_0} + \tau_s \left(\frac{A_s}{A_0} \right), \quad (3)$$

where F_v represents the frictional force (shear stress) exerted on the vegetation, A_0 denotes the total surface area of the ground, τ_s is the surface shear stress, and A_s is the surface area of the ground not covered by the vegetation.

Early works have employed the shear velocity ratio to define the threshold of wind erosion development (Raupach *et al.* 1993; Wolfe and Nickling 1996). Equation (3) can be rewritten mathematically as follows:

$$1 - \frac{F_v}{\tau_0 A_0} = \frac{\tau_s}{\tau_0} \left(\frac{A_s}{A_0} \right) = R^2 \left(\frac{A_s}{A_0} \right), \quad (4)$$

where R represents the ratio of the threshold shear velocity that indicates the effect of vegetation. R means the vegetation-induced fraction of wind stress, and an increase in its value indicates a proportional increase in susceptibility to wind erosion. Raupach *et al.* (1993) developed a prediction equation for the shear velocity ratio over vegetated surface as follows:

$$R = (1 - m\alpha\lambda)^{0.5} (1 + m\beta\lambda)^{0.5}, \quad (5)$$

where m is an empirical constant with a value between 0 and 1, indicating the unevenness of the soil surface, α is the object's aspect ratio, λ is the roughness density, and β is drag coefficient ratio between the object and soil surface.

3. Results and discussion

3.1 Canopy cover and geometry

Three aerodynamic parameters were in the present study introduced to describe the canopy characteristics, such as leaf area index (LAI), roughness density (λ), and coverage (C). LAI is a dimensionless quantity to characterize vegetation canopy, defined as the area occupied by leaves and branches on unit ground surface. Roughness density is widely used to evaluate the effects of vegetation on wind erosion that is the ratio of the frontal-silhouette area of canopy to the total surface area (Wolfe and Nickling 1993). As vegetation has a high porosity on its canopy, it is nearly impossible to accurately measure the canopy density by the silhouette area of vegetation (Loeffler *et al.* 1992). In the present study, the portion of pore space in the canopy was excluded in roughness density computation using the image analysis of side-view photographs of the vegetation. The percentage coverage represents the plan view area covered by vegetation on ground surface.

Aerodynamic parameters of the model canopies are summarized in table 2. Table 2 shows the values of leaf area index (LAI), roughness density (λ), and coverage (C) for each vegetation model used in the experiment. These values vary depending on the morphological characteristics of artificial plants and the experiment condition.

Canopy heights were measured to be 18 cm for Model A, 28 and 33 cm for Model B and C, respectively. LAI values ranged from 0.66 to 4.74 for the experimental conditions with Model A, while 0.50~3.55 in Model B and 1.24~8.84 in Model C. Roughness density for Model A varied from 0.09 to 0.65, according to the canopy arrangement. Model C has greater values in terms of LAI, λ , and C than Model A and B at the same arrangement, because of canopy morphology and its density.

As in the studies by Marshall (1971) and Minvielle *et al.* (2003), the Reynolds number was used to implement an experimental analogue to the field boundary layer condition. Reynolds numbers for a 60 cm tall shrub under wind velocities of 2~5 m/s are between 7.95×10^4 and 1.99×10^5 . The Reynolds numbers used in this study for a designed wind speed of 5 m/s ranged between 5.96×10^4 and 1.09×10^5 , and it thus demonstrates the aerodynamic similarity between the wind tunnel experiment and actual field condition.

3.2 The aerodynamic characteristics

The aerodynamic characteristics of canopy have been of interest in wind erosion processes for a very long time. Wind profile is one of the most important parameters to identify the degree and effectiveness of vegetation on wind erosion control. Figure 3 illustrates the vertical profile of the wind velocity for the three different arrangements of Model A. As shown in figure 3, canopy density has considerable influence on the height-dependent

wind velocity due to the effect of aerodynamic roughness. Model A-I is the most dense canopy for Model A with 4.74 of LAI, while Model A-VI has sparse canopy with 0.66 of LAI. Figure 3 apparently shows that wind speed through the canopy of Model A-I was nearly 1/4 of wind velocity above the canopy. In case of Model A-VI, a slight reduction of wind speed was observed within the canopy.

The relationship between roughness length and roughness density was also examined, as shown in figure 4. The value of normalized roughness length (Z_0/H) varied from 0.016 to 0.46 according to λ values. When λ value was greater than 0.11, the

Figure 3. Vertical profile of wind velocity for canopy model A. U_H represents the wind speed at a reference height H .

Figure 4. Relationships between normalized roughness length and roughness density.

Table 2. Aerodynamic parameters for wind tunnel experiments.

Canopy model	Height (cm)	Leaf area index	Roughness density	Coverage (%)
A-I	18	4.74	0.65	51.01
A-II		2.37	0.32	22.64
A-III		2.37	0.32	22.64
A-IV		1.33	0.18	12.68
A-V		0.95	0.13	9.06
A-VI		0.66	0.09	6.34
B-I	28	3.55	0.97	52.00
B-II		1.77	0.49	23.35
B-III		1.77	0.49	23.35
B-IV		0.99	0.27	13.08
B-V		0.71	0.19	9.34
B-VI		0.50	0.14	6.54
C-I	33	8.84	1.61	92.57
C-II		4.42	0.81	52.41
C-III		4.42	0.91	52.41
C-IV		2.48	0.51	38.98
C-V		1.77	0.37	27.84
C-VI		1.24	0.26	19.49

Z_0/H values were independent of the λ values, which is in accordance with the previous study (Raupach *et al.* 1991). In the experiments with Model A, Z_0/H values decreased slightly as λ values increased. Compared to wind tunnel study on creosote bushes (Hagen and Lyles 1988), all experiments for Model A generally showed similar trends to Z_0/H values, while experiments for Model B and C showed larger Z_0/H values than the previous study. These discrepancies were mainly due to the canopy characteristics, such as leaf morphology and flexibility. Marshall's (1971) study in figure 4 also shows that roughness density tends to have little effect on roughness length, when λ value is less than 0.002. This is due to the fact that airflow through vegetation canopy cannot be disturbed in relatively sparse vegetation cover.

Lee and Soliman (1977) classified vegetation canopy as three categories by the wind flow pattern depending on the λ value of canopy: isolated roughness flow ($\lambda \leq 0.082$), wake flow ($0.083 \leq \lambda \leq 0.198$), and skimming flow ($\lambda > 0.198$). Values of Z_0/H show little variation in the skimming flow regime with λ . The coefficients of variation were 0.32, 0.09, and 0.14 for Model A, B, and C, respectively, when $\lambda > 0.198$. In the wake flow regime, Z_0/H values were considerably variable with λ for Model A and B. Z_0/H values were estimated to be 0.356 and 0.142 in Model B, when $0.083 \leq \lambda \leq 0.198$. This difference is mainly due to determination of the zero-plane displacement height. According to the study by Raupach *et al.* (1980), the zero-plane displacement height can be underestimated owing to the diffusion of wake flow regime. The zero-plane displacement height can increase the Z_0/H value because of the increased roughness length estimated by the logarithmic law. Additionally, for ranges in which $\lambda \leq 0.198$, the Z_0/H value can be varied with the position of profile measurement because the horizontal wind velocity cannot be constant (Raupach *et al.* 1980).

3.3 The relationship between shear velocity and roughness density

Figure 5 presents the shear velocity ratio obtained from wind tunnel experiments of plastic vegetation. Therein, the field observation on creosote bushes conducted by Wolfe and Nickling (1996) and the results by Raupach *et al.* (1993) are juxtaposed into figure 5. It shows that Model A had a slightly higher shear velocity ratio than Model B and C. This demonstrated consequently that canopy types of Model B and C are more effective than that of Model A for protecting the soil surface from wind erosion.

Figure 5. Shear velocity ratios obtained from wind tunnel experiments. The dotted lines were obtained from equation (5) by Raupach *et al.* (1993).

Comparing the results of this study with those of Raupach *et al.* (1993), Model A shows similar values, whereas Model B and C have generally lower shear velocity ratios in most experiments. The results of Wolfe and Nickling (1996), also show slightly underestimated tendencies in some tests compared to that of Raupach *et al.* (1993). A previous finding reveals that shear velocity ratio derived from the experiment with lower wind velocity tends to be underestimated, compared to the values with high wind velocity (Wolfe and Nickling 1996). They used field measurements in which the average wind speed at a height of 10 m exceeded 5 m/s.

Vegetation can cause to increase drag force as wind velocity decreases, and this leads to increase in shear velocity, which in turn decreases the shear velocity ratio. The wind velocity applied in our experiments was 5 m/s, which is less than the threshold wind velocity typically associated with wind erosion in vegetation environments. This may explain the underestimated results of the present study compared to those of Raupach *et al.* (1993).

It is acknowledged that vegetation absorbs momentum from airflow by individual leaf elements and branches. The momentum absorbability depends on geometry, flexibility, and porosity of canopy. Gillies *et al.* (2002) found that drag force had a linear relationship with wind speed in lower flexible canopy. With increased plant flexibility, it appeared that the linear relationship was not valid but power function relationship would rather be observed.

3.4 Shear stress partitioning

Figure 6 shows the relationship between shear stress partitioning and roughness density. The shear stress partitioning for canopy Model A

Figure 6. Relationship between shear stress partitioning and roughness density.

ranged from 0.03 to 0.14. The values for Model B and C varied from 0.01 to 0.06, and from 0.00 to 0.25, respectively. Similar to the shear velocity ratio, shear stress partitioning decreased as λ values increased. When λ values were greater than 0.2, the partitioning came nearly zero. The shear stress partitioning was found to be lower in Model B and C compared to Model A for similar λ values.

Wind speed can be dramatically reduced in long narrow canopies (Model A) as vegetation density increases. Even though a high value of shear stress ratio was estimated in the lowest canopy density of Model C, canopy density has slight influence on airflow in round leaves and stalks canopies. It is because the wide surface of round leaves in Model B and C can broadly influence airflow in sparse density, while long narrow leaves have obstacle effect on airflow in just near or behind canopy.

Marshall (1971) calculated the roughness density value using the relationship between shear stress partitioning and roughness density by ignoring the shear stress exerted on the ground. It was found that the effects of decreased shear stress become constant, when λ exceeds a certain value. Therefore, this constant value can be parameterized for quantifying the buffering effect of vegetation on wind erosion. In the present study, wind erosion buffering effects were found to be greater in canopy model B and C than in model A.

4. Conclusions

Wind erosion poses serious problems and considerable threat in most regions of the world. Vegetation on ground surface has an important role in controlling wind erosion by sheltering soil surface and absorbing flow momentum. In this study, wind tunnel experiments were performed to quantitatively explore the effect of canopy structure on wind movement. Three types of artificial vegetation

were employed in the experiments as model canopy, which have well-defined porosity and flexibility. Estimates of wind profile, roughness length, and shear stress partitioning were compared according to vegetation model and arrangement.

Experiment results showed that as roughness density (λ) reaches the maximum value ($\lambda_{\max}$), normalized roughness length, Z_0/H (where H means canopy height), increases, while R values decreases. Beyond the value of $\lambda_{\max}$, both Z_0/H and R values showed little change as λ increases. This conforms well to previous researches. Derived R value were also compared to the prediction by Raupach *et al.* (1993) model. Values obtained from the experiments seem to be slightly overestimated, but were relatively similar to the values estimated by Raupach *et al.* (1993) model.

The study has provided some insights on the behaviour of wind movement over vegetated surface. However, the results are limited to the model canopy and the applied wind speed for exploring the stabilizing role of vegetation on wind erosion. And therefore, for deeper understanding of the effects of vegetation cover and patterns on wind erosion, further experiment should be conducted with well-shaped natural vegetation under controlled conditions.

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