



The response of live plants to airflow – Implication for reducing erosion

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ARTICLE INFO

Keywords:

Cosmos bipinnatus

Ligustrum lucidum Ait

Plant morphology

Form response

Aerodynamic characteristics

Live plant

Wind tunnel

ABSTRACT

The form response of a plant to airflow is a critical factor influencing plant resistance to strong winds and thus the effectiveness of vegetation in reducing wind erosion. As this response is determined by the morphology of the plant and is different in different plant species, the responses of two morphologically different plants to airflow were investigated in wind tunnel experiments. The aerodynamic characteristics of frontal area (FA), optical porosity (OP), frontal area efficiency (FA_{eff}) and wind drag force (F_D) in a range of wind velocities were determined for narrow-leaved *Cosmos bipinnatus* and broad-leaved *Ligustrum lucidum* Ait. FA and OP reflect a plant's ability to absorb momentum and allow throughflow, and changes in both measures are linked to wind velocity. In higher wind velocities, FA and OP of both plant types decreased, although *L. lucidum* lost less frontal area and more porosity than *C. bipinnatus*. E values (a reconfiguration measure of changes in form) were greater and F_D values were less for *C. bipinnatus* than for *L. lucidum*. As broad-leaved *L. lucidum* provided a greater resistance to strong winds than *C. bipinnatus*, investigating the aerodynamic properties of suitable broad-leaved plants for erosion control in arid lands is recommended.

1. Introduction

Vegetation as a roughness element plays a crucial structural and functional role in controlling sediment transported by wind (Wolfe and Nickling, 1993) and has been used to control wind erosion around the world in the form of cover crops and wind strips (Dong et al., 2001). Vegetation increases surface roughness and protects the soil surface by extracting a portion of the total momentum imparted by air flow (Musick and Gillette, 1990; Dong et al., 2001). A better understanding of vegetation reaction to airflow is necessary in developing our knowledge of wind velocity patterns in the context of aeolian erosion control. Analysing the interaction of wind and vegetation at various scales is essential for assessing the local turbulence environment and the wind forces acting on plants (Finnigan and Brunet, 1995; Raupach et al., 1996; Dupont and Brunet, 2008). Such analysis produces an understanding of how plants respond to various wind speeds by potentially changing their aerodynamic characteristics, including frontal area and porosity.

Porosity of vegetation, defined as the ratio of pore space to the space occupied by plant stems, branches, twigs and leaves, is a critical indicator of vegetation structure that determines the rate of airflow passing through the plant (Humberto and Rattan, 2010). Porosity is a

commonly used descriptor for the internal structure of artificial wind-breaks and has been explored by many researchers (e.g. Hagen and Skidmore, 1971; Plate, 1971; Heisler and Dewalle, 1988; Zhu and Jiang, 1992; Středová et al., 2012). A two-way interaction can be observed between wind and porosity of plants: wind influences the porosity of plants, and porosity influences the proportion of airflow which can pass through the plants. Depending on the aerodynamic and structural characteristics of vegetation, porosity is influenced by wind speed and decreases exponentially with increasing wind velocity (Gillies et al., 2002). Due to this interaction, porosity should be considered in assessing the ability of different plants to reduce wind velocity.

In practice, the physical measurement of aerodynamic porosity is difficult because it does not take into account the three-dimensional nature of the pores in natural plants (Heisler and Dewalle, 1988; Vigiak et al., 2003). Optical porosity, a two-dimensional measure of porosity, has been defined as a practical alternative to aerodynamic porosity even though it is not an equivalent measure (Heisler and Dewalle, 1988; Sturrock, 1969; Vigiak et al., 2003; Bitog et al., 2011; Středová et al., 2012). In addition optical porosity can be a useful indicator to evaluate the shelter effect and efficiency of windbreaks and to predict wind profiles (Loeffler et al., 1992; Santiago et al., 2007; Li and Sherman,

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2015; Nosek et al., 2016; Wu et al., 2018). Gillette et al. (2006) used optical porosity to determine the penetrability of mesquite bushes and mesquite coppices by wind and related larger optical porosity of mesquite bushes (or coppices) to greater permeability. They indicated that optical porosity provides a qualitative index of whether airflow passes through or around and over the mesquite. Raupach et al. (2001) recognised that for a given wind velocity, the penetration level of airflow into a vegetative canopy is correlated with optical porosity. Estimation of optical porosity has been developed by photographic techniques (Maki and Allen Jr, 1978; Kenney, 1987; Heisler and Dewalle, 1988; Loeffler et al., 1992; Gillies et al. 2002; Zhu et al., 2003; Lampartová et al. 2015; Yang et al., 2017; Rehacek et al., 2017; Wu et al., 2018).

When plants are subjected to high wind speed (high drag force), their flexibility operates as a deformation mechanism which allows them to change their shape or reduce their projected area perpendicular to the wind both by bending and twisting and by reconfiguring and becoming more streamlined (Vogel, 1981; Harder et al., 2004). This mechanical response assists plants to withstand high wind loads without damage by reducing the drag force. For example, tuliptree or red maple leaves reconfigured into a cone shape, thereby reducing the exposed surface area to wind and enabling a reduction in the drag force (Vogel, 1989). When daffodils were exposed to high wind velocity, the stem of each flower head was bent close to the ground surface, thereby becoming subjected to less drag force (Etnier and Vogel, 2000).

Many experimental measurements on the reconfiguration of plants have been made because of applications in biology, agriculture and forestry which include plant adaptation, predicting and preventing the phenomenon of lodging, wind-throw prediction models and understanding plant susceptibility to wind damage (Berry et al., 2004; Harder et al., 2004; Rudnicki et al., 2004; Vollsinger et al., 2005; Vogel, 2009). Reconfiguration of plants has been investigated in the field (Grant and Nickling, 1998; Kane et al., 2008; Koizumi et al., 2010), in wind tunnels (Gillies et al., 2002; Rudnicki et al., 2004; Vollsinger et al., 2005; Ishikawa et al., 2006; Cao et al., 2012) and in water flumes (Boller and Carrington, 2006; Albayrak et al., 2010; Albayrak et al., 2012). Because plants have different dynamical structures they present varying modifications when subjected to wind. The ability of reconfiguration is defined by the E value suggested by Vogel (1984, p. 39). Reconfiguration has been studied for different plants; for example, the E values of smaller broadleaf deciduous trees are similar to the E values of larger conifers ($E \sim -0.71$) (Kane et al., 2008), indicating the same degree of deformation of both plants. However, different E values were obtained for *Ilex crenata*, *Hibiscus syriacus* and *Thuja occidentalis* when they were subjected to a range of wind speeds (Cao et al., 2012), pointing to different amounts of reconfiguration between these plant types which was attributed to morphological differences. Other variables may contribute to plant responses, including health, age, environmental conditions and seasonality but these factors can be more readily controlled in wind tunnel experiments than under field conditions.

Decrease in a plant's frontal area as a function of wind speed and direction is an important aerodynamic characteristic resulting from reconfiguration which allows for a reduction in wind load. Generally, the change in frontal area would vary between plant types depending on their flexibility. Some plants have a tendency to present their maximum frontal area at low to moderate wind speeds until a threshold is reached, when any further increase in wind velocity forces a decrease in their frontal area (Middleton and Southard, 1984). This response was observed in Burning Bush (*Euonymus alatus*) and Colorado Blue Spruce (*Picea pungens glauca*) (Gillies et al., 2002). In other plants such as *Acer macrophyllum* and *Alnus rubra*, frontal area remained constant at low wind speeds and then decreased rapidly with increasing wind velocity (Vollsinger et al., 2005). The patterns of change with increasing wind speeds thus differ between plant types. *Pennisetum setaceum* (Gillies et al., 2002), *Hibiscus syriacus* and *Thuja occidentalis* 'Smaragd' (Cao et al., 2012) showed a steady decline in frontal area. Vollsinger et al.

(2005) subjected three hardwood species to wind velocities from 4 to 20 m s⁻¹ to assess plant susceptibility to wind force damage and found that the frontal area decreased to 20–37% of its initial value at a wind velocity of 20 m s⁻¹. Rudnicki et al. (2004) exposed three morphologically different conifers to wind speeds from 4 to 20 m s⁻¹ and observed that at 20 m s⁻¹ the frontal area of the *Pinus contorta* species reduced by 36–54%. In contrast, Japanese Holly (*Ilex crenata*) did not present a change in its frontal area when wind velocity increased (Cao et al., 2012). Similar to frontal area, the porosity of plants can be altered in a normal or complex response as the result of deformation. Gillies et al. (2002) reported increasing porosity for Burning Bush (*Euonymus alatus*) and Colorado Blue Spruce (*Picea pungens glauca*), and decreasing for Fountain Grass (*Pennisetum setaceum*), with increasing wind speed.

Various plants with different aerodynamic characteristics and designs present various form responses to wind. The rate of reconfiguration, flexibility and plant drag coefficient are determining factors influencing plant efficiency in extracting drag force and affecting wind velocity and subsequent potential airborne sediment transport; and responses can be influenced by plant design and morphology. However, in some cases, differences in aerodynamic forms of plants result in similar responses to wind. For example, even though the dynamic structures of *Hibiscus syriacus* and *Thuja occidentalis* are different, they presented the same reconfiguration value when subjected to wind. The deformation of these plants differed from *Ilex crenata* because of different dynamical forms (Cao et al., 2012). Kane et al. (2008) observed the same reconfiguration in smaller broadleaf deciduous trees as in larger conifers. Gillies et al. (2002) subjected three plant species (*Euonymus alatus*, *Picea pungens glauca* and *Pennisetum setaceum*) with different aerodynamic forms to a range of wind velocities and observed different form responses of the plants in reducing drag, frontal area and porosity.

Lower wind speeds, whether present as steady stream or turbulent air flows, are generally associated with reduced risks of aeolian erosion. In this study, wind tunnel experiments were conducted to assess morphologic and aerodynamic responses of two types of live plants to a range of wind speeds. Although the plants species used in the current study cannot be utilized to reduce wind speed and control aeolian erosion in arid zones, they provide a new view of vegetation characteristics that need to be considered in wind erosion control. In addition, the results can be used for establishing suitable natural vegetative barriers. Although related wind tunnel studies have been carried out, this investigation is focussed on determining which of two morphologically dissimilar plant types is more effective in reducing wind velocity and thereby assisting in controlling sediment detachment and transport. By subjecting plants of *C. bipinnatus* and *L. lucidum* to a range of wind speeds, the morphologic and aerodynamic responses of these structurally and morphologically different plants were assessed for their ability to intercept damaging winds.

2. Materials and methods

The wind tunnel of the Key Laboratory of Environmental Dynamics on the Loess Plateau, at the Shanxi Normal University in Xi'an, China was used to conduct the experiments. The experimental section of the wind tunnel was 7 m long, 0.5 m wide and 0.6 m high (Fig. 1).

Two different types of live plants with different morphology and structure were selected, namely *Cosmos bipinnatus* and *Ligustrum lucidum* Ait. *C. bipinnatus* is a medium-sized flowering herbaceous medicinal plant (Dubey and Singh, 2011) which varies in height from 0.6 to 2 m. It belongs to the Asteraceae or Compositae family and came originally from Arizona and central Mexico (Leslie, 2005). *L. lucidum* is a fast-growing evergreen large shrub or small shrubby tree belonging to the Oleaceae family, growing 4–12 m tall (Nelson et al., 2014). The plants of both types used in this study were seedlings with a height of about 0.15 m. The major morphologic difference between the plants is their leaf structure: *C. bipinnatus* has narrow leaves and *L. lucidum* has

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