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Relationships between shelter effects and optical porosity: A meta-analysis for tree windbreaks

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ABSTRACT

The impact of tree windbreaks on air flow remains poorly understood in field conditions. Porosity (ϕ), an indicator of tree windbreak structure, has often been used to explain shelter effects, but its relationship with shelter effects has not been consistent and even contradictory among studies. Here, we compiled a global dataset on shelter effects and optical porosity from published field studies for tree windbreaks. We found that shelter effects, including minimum relative wind speed (U_m/U_0), average reduction of relative wind speed (R) and effective shelter distance (D_{70}), displayed a good linear relationship with optical porosity. External characteristics of tree windbreaks (width, number of row, height, and forest type) explained 36.1% of the total variation of optical porosity, and these characteristics modulated the relationships between shelter effects and optical porosity. An optimal optical porosity (ϕ = 20–40%), with best shelter effects, was found for tree windbreaks with one row, which should provide some practical guidance for windbreaks construction. The failure to find an optimal optical porosity for tree windbreaks with multiple rows suggested some indices that could express 3-D structure should be developed and used for tree windbreaks with width dimension. Our study is the first that reveals the relationships between shelter effects and optical porosity for tree windbreaks using a global dataset, which should advance our understanding on structure and function of tree windbreaks.

1. Introduction

Shelterbelts are designed for a variety purposes, including wind or water erosion control, snow management, animal production and farmhouse protection (Zhu, 2008; Lee et al., 2014; He et al., 2017). Windbreaks, designed for wind and soil erosion control, are one of the most important shelterbelts types, and relationships between structure and shelter effects has been widely studied on windbreaks (Brandle et al., 2004; Torita and Satou, 2007; Streda et al., 2008; Wu et al., 2013; Rehacek et al., 2017). Porosity, defined as the percentage of open space of the windbreak to its total volume, is a common descriptor for the structure of windbreaks (Jiang et al., 1994; Nosek et al., 2016). It is frequent expressed as optical porosity (percentage of open spaces as seen perpendicularly to the windbreak side) in most studies (Streda et al., 2008; Lampartova et al., 2015). For windbreaks, shelter effects are usually expressed as wind speed reduction at their leeward side (e.g., minimum wind speed, reduction in wind speed) and shelter distance (e.g., effective shelter distance) (Torita and Satou, 2007; Wu et al., 2013). Previous studies quantified the relationships between shelter effects and porosity of windbreaks (Streda et al., 2008; Ian et al., 2009; Li and Sherman, 2015; He et al., 2017), and found that these relationships were quite variable and likely depended on windbreaks types (e.g., forest, fence, plastic model and barrier) and study methods (e.g., field monitoring, numerical simulation and wind tunnel).

Many studies found that the relationships between shelter effects and porosity depended on the type of windbreaks. For shelter fence, model or barrier, with no significant width dimension, optical porosity has been used successfully to predict the wind profile and their shelter effects (Santiago et al., 2007; Li and Sherman, 2015; Nosek et al., 2016). For tree windbreaks, with both width dimension and uneven vertical structure, optical porosity is more complex to quantify, and its relations to shelter effects becomes highly variable and difficult to

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predict (Zhu et al., 2003a, 2003b, 2004; Zhang, 2017). Some studies found that shelter effects were worse for windbreaks with lower (< 20%) and higher values (> 60%) of optical porosity (Rehacek et al., 2017), suggesting that the best shelter effects would be found at an optimal optical porosity with a medium value (Grant and Nickling, 1998; Cornelis and Gabriels, 2005; Ian et al., 2009). For example, optimal optical porosity value of 0.25 was reported for *Populus* windbreaks (Jiang et al., 1994; Zhu et al., 2002). In contrast, other studies reported a linear relationship (Loeffler et al., 1992; Schwartz et al., 1995; Bird et al., 2007; Stredova et al., 2012) or no relationship (Thuyet et al., 2014) between shelter effects and optical porosity. These inconsistent results may be attributed to the impact of external characteristics (e.g., width, height, forest type) on optical porosity for tree windbreaks. For example, previous studies have speculated that optical porosity is considered as a good descriptor for narrow tree windbreaks, but it is not suitable for tree windbreaks with width dimension (Nord, 1991; Stredova et al., 2012; Wu et al., 2013). However, this speculation has not yet been supported by relationships between shelter effects and optical porosity.

Relationships between shelter effects and porosity also showed differences among study methods. Shelter effects (wind and soil erosion) was easy to obtain and showed good relationships with porosity or structure of windbreaks in wind tunnel or numerical simulation (Lee et al., 2002; Zhang, 2017). However, the impact of windbreaks on air flow turbulence remains poorly understood in field conditions where the dynamic complexity of the air flow structures cannot be controlled in the same way as in wind tunnel environments or simulation studies (Mayaud et al., 2016; Zhang, 2017). Furthermore, both shelter effects and optical porosity were difficult to measure in field experiments due to differences in windbreaks type, underlying land surface, monitor equipment (Zhou et al., 2004; Thuyet et al., 2014). Therefore, the relationships between shelter effects and optical porosity are poor and variable for tree windbreaks in field conditions.

To clarify the relationship between shelter effects and optical porosity, we compiled a global dataset on external characteristics, optical porosity, and shelter effects, which were all determined in the field for tree windbreaks. Based on the dataset, we 1) quantified the relationships between shelter effects and optical porosity; 2) determined if there exists an optimal optical porosity; 3) tested how external characteristics affected the relationships between shelter effects and optical porosity for tree windbreaks.

2. Methods

2.1. Data collection

We collected a global dataset that included 299 data points on the following variables: external characteristics (width, number of row, height, forest type), porosity (optical porosity), and shelter effects (minimum relative wind speed, average reduction of relative wind speed, effective shelter distance, and absolute effective shelter distance) (Appendix Table in Supplementary material). The data were derived from 49 studies, which were selected by searching the following databases: Web of Science, Google Scholar, Chinese National Knowledge Infrastructure (CNKI), and monographs. We also included our own unpublished data. A summary of the dataset is given in Table 1.

2.1.1. Definition of variables used in the study

Porosity (ϕ, %) is essentially the fraction of open spaces within a windbreak. Porosity may be determined by different methods, but only optical porosity data were included in our study.

Wind speed (U, m s^{-1}) is monitored in the open area (control), and the windward and leeward sides of windbreaks. Only the data with wind speed monitored below 2 m height were included.

Minimum relative wind speed (U_m/U_0, %) is the ratio of the minimum wind speed (U_m) in the lee to the wind speed at the reference point or open area (U_0).

Table 1
A summary on optical porosity, variables that described shelter effects and external characteristics of tree windbreaks.

	Sample size	Minimum	Maximum	Average	Coefficient of variation %
Porosity					
Optical porosity (%)	299	1.0	87.9	35.4	52.4
Shelter effects					
U_m/U_0 (%)	185	7.1	83.0	42.1	41.5
R (%)	201	2.2	66.0	32.2	38.2
D_{70} (H)	174	0.5	29.3	8.3	33.0
D (m)	122	13.0	460.0	137	64.9
External characteristics					
Number of row	189	1.0	25	3.4	76.4
Height (m)	201	1.4	26.0	11.5	43.0

Average reduction of relative wind speed (R, %) is the average reduction in ratio of wind speed (U) in the lee to U_0,

$$R = 1\text{-}\frac{1}{j}\sum_{1}^{j}\frac{U_j}{U_0}$$

R, average reduction of relative wind speed; j, the distance of measurement from the lee of a windbreak; U_j, wind speed at the j position in the lee.

Effective shelter distance (D_{70}, H) is the distance over which the wind speed U in the lee does not exceed 70% of U_0, and expressed in proportion to height (H) of windbreaks.

Absolute effective shelter distance (D, m) is defined as $D_{70} \times H$.

2.2. Data analysis

Regression analysis was performed to test the relationships between shelter effects and optical porosity. Hierarchical partitioning (HP) analysis was used to examine the effects of external characteristics on optical porosity of tree windbreaks. Tree windbreaks were separated into groups based on number of row (associated closely to width): one row and multiple rows; height: < 15 m and ≥ 15 m; forest type: broadleaved forest (BF), coniferous forest (CF) and mixed forest (MF). The height of 15 m was decided as a threshold because there existed an inflexion point in the curve relationship between R and height (Appendix Figure in Supplementary material). Standardized Major Axis slope (SMAs) was also used to test for statistical differences among regression lines between shelter effects and optical porosity for tree windbreaks with different external characteristics.

All analyses were performed using R statistical platform 3.3.0 (R Development Core Team).

3. Results

3.1. Relationships between shelter effects and optical porosity

Minimum relative wind speed (U_m/U_0) increased with increasing optical porosity (R^2 = 0.298, P = 0.000) (Fig. 1a); average reduction of relative wind speed (R) and effective shelter distance (D_{70}) decreased linearly with increasing optical porosity (R^2 = 0.175, P = 0.000; R^2 = 0.127, P = 0.000) (Fig. 1b and c). However, there was no relationship between absolute effective shelter distance (D) and optical porosity (Fig. 1d).