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Effects of species and shelterbelt structure on wind speed reduction in shelter

Dang Van Thuyet · Tran Van Do · Tamotsu Sato · Trieu Thai Hung

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Abstract Live shelterbelts are common elements in coastal land areas and play an important role in reducing wind speed and sand drift. A simple measured index, that well represents relationship between shelterbelt structure and wind speed reduction, is required by landowners to enable them in establishing more effective shelterbelts. A three-dimensional crown (3D) density is proposed, which can be easily identified through shelterbelt parameters including maximum height, shelterbelt width, vertical crown/stem area ratio, and horizontal crown/stem area ratio. The utility of the index was tested in 10-year-old *Casuarina equisetifolia* and in 7-year-old *Acacia auriculiformis* shelterbelts in north central Coast of Vietnam. There was a significant negative linear relationship ($R^2 = 0.64$, $p < 0.001$) between 3D density and wind speed reduction efficiency, while there was no relationship between a two-dimensional crown density and wind speed reduction efficiency. Reduction efficiency was found to increase at higher wind speeds in shelterbelts of *A. auriculiformis*, but not *C. equisetifolia*. The *A. auriculiformis* shelterbelt was more efficient in reducing wind speed compared to *C. equisetifolia* shelterbelt. The former recovered 70 % wind speed at 130 m (16.5H) leeward, while it recovered 70 % at 85 m (8H) leeward in *C. equisetifolia* shelterbelt.

Keywords Horizontal structure · Relative wind speed reduction · Shelterbelt · Three-dimensional crown density · Vertical structure

D. Van Thuyet (✉) · T. Van Do · T. Thai Hung
Silviculture Research Institute, Vietnamese Academy of Forest Sciences, Hanoi, Vietnam
e-mail: dangvanthuyet@yahoo.com

T. Van Do
JSPS fellow, Forestry and Forest Products Research Institute, Tsukuba, Japan

T. Van Do · T. Sato
Department of Forest Vegetation, Forestry and Forest Products Research Institute, Tsukuba, Japan

T. Thai Hung
Tasmanian Institute of Agriculture/School of Agricultural Science, University of Tasmania, Hobart, Australia

Introduction

Shelterbelts or windbreaks, even in a single species and/or single row, play a significant role in reducing damage from wind (Santiago et al. 2007). Most windbreaks in many countries have been primarily established for expanding or increasing agricultural production (Cao 1985; Zhao et al. 1995; Wu et al. 2013), other benefits of windbreaks are increasingly being recognized as reducing soil erosion, sand drift, protecting crops, livestock and farmstead, and providing wildlife habitat (Bird et al. 1992; Smith et al. 1998; David and Rhyner 1999; Leon and Harvey 2006).

The reduction of wind speed in the protected areas behind a shelterbelt is because that the shelterbelt exerts a drag force on the wind field, leading to loss of momentum of the airflow (Plate 1971). As result of reducing wind speed, microclimates in protected areas are also altered. The wind flow modification of a particular shelterbelt or multiple shelterbelt system is dependent on its structure (Heisler and DeWalle 1988) such as width, length, shape (Vigiak et al. 2003; Lee 2010), and porosity (Zhou et al. 2004; Santiago et al. 2007). Therefore, structure of shelterbelt may be designed differently to meet objectives of landowners (Woodruff et al. 1963).

Two-dimensional (Zhu et al. 2003; Zhang et al. 1995b) and three-dimensional (Zhou et al. 2004) porosities are useful indicators representing shelterbelt structure. Two-dimensional porosity is defined as the ratio or percentage of pore space to the space occupied by tree stems, branches, twigs, and leaves on photograph of shelterbelt length and height, while three-dimensional porosity is identified basing on a cubic of shelterbelt length, height, and width. However, optical porosity is difficult to identify (Torita and Satou 2007) and always results in less than actual values especially for wide shelterbelts (Sudmeyer and Scott 2002). A simple measured three-dimensional crown (3D) density, which can be easily measured based on shelterbelt parameters as width of shelterbelt (W), tree height (H), total vertical crown/stem area ratio (C_v), and total horizontal crown/stem area ratio (C_h) in a unit of shelterbelt length (1 m), is proposed in the present study. The objectives of the present study were to quantify the relationship between 3D density and wind speed reduction efficiency and to compare wind speed reduction effectiveness of *Casuarina equisetifolia* Forst et Forst.f. and *Acacia auriculiformis* A. Cunn shelterbelts in north central Coast of Vietnam.

Casuarina equisetifolia, belonging to the family Casuarinaceae, distributes naturally from Burma, Vietnam to south Australia. This is an evergreen, dioecious or monoecious tree 6–35 m tall, with a finely branched crown. Crown shape is initially conical but tends to flatten with age. Trunk is straight, cylindrical, usually branchless for up to 1/3 stem tall. The minute, reduced, toothlike leaves are in whorls of 7–8 per node. *Acacia auriculiformis*, belonging to the family Fabaceae, is origin from Australia, Papua New Guinea, and Indonesia. This is an evergreen, unarmed tree to 15 m tall, with compact spread, often multi-stemmed. Leaves are bladelike, slightly curved, and 10–20 cm long.

Study sites and methods

Study sites

There are ~0.5 million ha sandy land areas, distributing from 21°40′N to 8°30′N along coastal area of Vietnam (Phan 1987). Of which, nearly 0.14 million ha is located in north central Coast (Fig. 1). In central Coast, about 20 ha of agriculture land is encroached by sand drift annually (Nguyen 2002). The most effective method is establishing live shelterbelts along coastal areas for reducing wind speed. As a result, a number of shelterbelts have been established throughout Vietnam, however much were focused on central Coast, where high wind speed and dunes have much affected on agricultural activities (Pham 2002).

The present study was conducted in north central Coast at Trieu Lang (TL; 210 m far from sea) and Hai An (HA; 175 m far from sea) communes of Quang Tri province and at Quang Loi (QL; 2,500 m far from sea) commune of Thua Thien Hue province (Fig. 1). There are no fenders from the sea to shelterbelt at TL and HA, while scattered trees, villages etc. are fenders to shelterbelt at QL. *C. equisetifolia* was used for shelterbelt establishment at TL and HA, which was 10 years old. While *A. auriculiformis* was used at QL, which was 7 years old. The general shelterbelt parameters are shown in Table 1.

Data collection

At each study site, seven plots (plot length (L) = 30 m and plot width (W) = shelterbelt width; Table 1) were selected systematically at 50–80 m intervals in the shelterbelt. Tree growth parameters were measured including height (H in m), crown length (L_c in m), diameter at breast height (DBH in cm), and crown diameter (C_d; east–west, north–south in m). Vertical (perpendicular to shelterbelt width) and horizontal crown/stem area of all stems in surveyed plots were drawn at scale of 1:60, which were used to calculate ratios of total vertical and horizontal crown/stem area in each plot.

Wind speed was measured by using portable Kestrell 3000 at 1.5 m above ground. The poles of

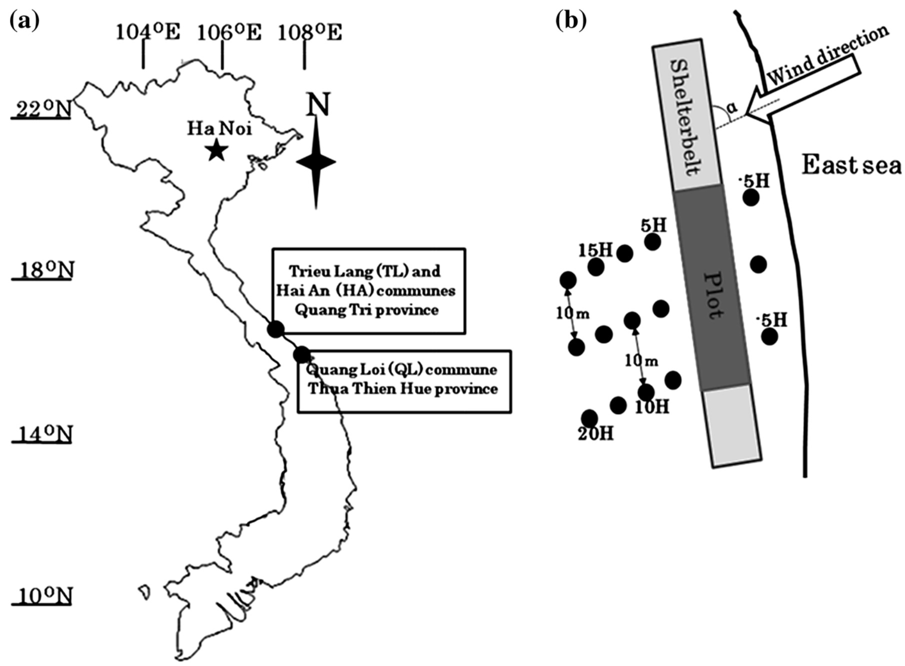

Fig. 1 The location of study sites (**a**) and monitoring positions (**b**). α is angle of northeast wind to shelterbelt, ranging from 80 to 90 °. Leeward speed was recorded only at 5H and 10H at HA site

1.9 m long and 3 cm diameter were fixed 40 cm to ground for stabilizing Kestrell 3000 on the tops. Fifteen units of Kestrell 3000 were used to record data for all positions simultaneously (Fig. 1b). There are two types of wind in study sites as northeast wind (October) and southeast wind (May). However, northeast wind is usually stronger and accompanies with coldness from the north, which has adverse effects on crop's growth and productivity. The data were recorded for 15 consecutive days (five days per each site) in October (northeast wind; 80–90 degree to shelterbelt; Fig. 1b) at 7, 8, 9, 10, 11, 13, 14, 15, 16, 17. At each hour, mean value from five times recorded in 12 min intervals was used. The positions including windward (−) and leeward used for wind speed measuring are shown in Fig. 1 and Table 1, depending on height of studied shelterbelts. Leeward speed was recorded at 5, 10, 15 and 20H for TL and QL, and only at 5 and 10H for HA, because of unavailability of equipment. Windward and leeward positions were located in lines parallel to wind direction (Fig. 1).

Data analysis

3D density (D_3; m^3) of shelterbelt was calculated for all surveyed plots following Eq. 1

$$D_3 = H * W * C_v * C_h * 1 \quad (1)$$

where H is maximum height of shelterbelt in meter, W is width of shelterbelt in meter, C_v is ratio of total vertical crown/stem area, C_h is ratio of total horizontal crown/stem area, and 1 is standardized in 1 m length of shelterbelt.

$$C_v = \frac{\sum_{i=1}^{n} C_{v_i}}{H * L} \quad (2)$$

where C_{vi} is vertical crown/stem area of stem ith in surveyed plot, L is length of surveyed plot (30 m; Table 1).

$$C_h = \frac{\sum_{i=1}^{n} C_{h_i}}{W * L} \quad (3)$$

where C_{hi} is horizontal crown/stem area of stem ith in surveyed plot, W (width of surveyed plot) equals to width of shelterbelt (Table 1).

2D density (D_2; m^2) was calculated as $D_2 = H * C_v * 1$

The relative wind speed at each leeward position equaled U/U_o, where U_o is windward speed at −5H and U is leeward speed (Zhang et al. 1995a). Linear regression was used to fit relationships between D_2 and

D_3, and U/U_o. While saturation curve was used for relationship between leeward distance and U/U_o. SAS package was adopted for statistical analysis.

Results

Windward speed at −5H differed among the study sites (Table 1). It was highest for the HA site, where distance from shelterbelt to the sea was 175 m. It was lower at TL site with a distance of 210 m to the sea. Even much further from the sea (2,500 m), windward speed at QL site was quite high, up to 5.1 m s^{-1}, however the lowest speed (0.4 m s^{-1}) was also measured, representing high variation of wind speed. Data were recorded at different days for each site (HA, TL, and QL), however all recorded dates were on peak wind speed days of northeast wind (Dang 2004). Therefore, different windward speeds at −5H among study sites resulted from the differences of distance to the sea. Those figures indicated the complexity of wind regime in the study sites.

Although *C. equisetifolia* was the same age of 10 years old, growth parameters (DBH, H, L_c, C_d) of the shelterbelt at TL site were generally higher than that at HA site (Table 1). However, because of higher stem density (2,200 ha^{-1}) and wider shelterbelt (90 m), it led to higher 3D density (D_3) at HA compared to TL, but 2D density (D_2) was not. Shelterbelt at QL had highest stem density of 2,645 ha^{-1} but narrowest width of only 4 m, leading to lowest values of D_3. But because of high L_c/H ratio it led to highest values of D_2 (Table 1).

There were no relationships between windward speed at −5H and U/U_o at 5H at TL and HA sites (Fig. 2a, b, c), where *C. equisetifolia* was used for shelterbelt establishment. While, it was negative linear relationship ($R^2 = 0.6$, $p < 0.001$) at QL site, where *A. auriculiformis* was used (Fig. 2d). There was high variation of U/U_o at HA site, when wind speed at −5H (U_o) reached greater than 6 m s^{-1} (Fig. 2b). Since HA site locates 210 m far from sea leading to unsteady state of wind speed and direction. In addition, special leaf morphology like needles (the minute, reduced, toothlike leaves) and crown shape *C. equisetifolia* were also responsible for such variation. In contrast, the higher windward speed at −5H, the more efficiency of wind speed reduction at 5H leeward at QL site located 2,500 m far from sea (Fig. 2d). This

Table 1 The general parameters of shelterbelts and windward speed at −5H at Hai An (HA), Trieu Lang (TL), and Quang Loi (QL) study sites

Study site	Range of wind speed at −5H (m s^{-1})	Distance from the east sea to shelterbelt (m)	Surveyed plot dimension [width/W (m) × length/L (m)]	Planted species, number of planted lines, shelterbelt age (years)	Current density (stems ha^{-1})	Growth parameters				Density parameters				
						DBH (cm)	H (m)	L_c (m)	C_d (m)	Shelterbelt width (W in m)	Vertical crown/stem area ratio (C_v)	Horizontal crown/stem area ratio (C_h)	3D crown density (D_3; m^3)	2D crown density (D_2; m^2)
HA	2.1–6.8	175	90 × 30	*C. equisetifolia* 40, 10	$2{,}200^a$	8.6^a	9.2^a	5.6^a	3.1^a	90	0.8^a	0.4^a	256^b	7.4^a
TL	1.8–5.3	210	26 × 30	*C. equisetifolia* 8, 10	$1{,}700^b$	10.4^b	10.9^b	7.5^b	3.4^b	26	0.7^a	0.3^a	60^a	7.6^a
QL	0.4–5.1	2,500	4 × 30	*A. auriculiformis* 3, 7	$2{,}645^c$	6.9^c	7.8^c	6.3^c	2.5^c	4	1.7^b	0.8^b	43^c	13.3^b

Different letters in a column indicate the difference of mean by *t* test at 95 % confidence

DBH diameter at breast height, *H* stem height. L_c length of stem crown. C_d diameter of stem crown

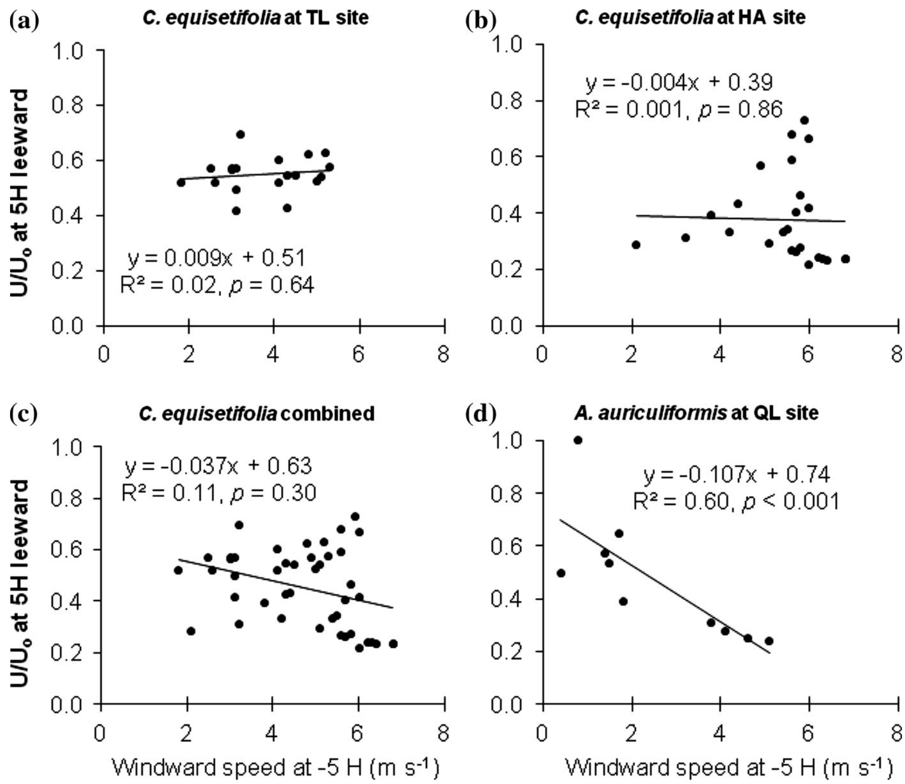

Fig. 2 Relationship between windward speed at -5H and U/U_o at 5H leeward

may be resulted from the fact that windward speed at -5H (U_o) was much simple as maximum speed of 5.2 m s^{-1}, and steady state and direction of windward speed at QL site compared to that at HA site.

The saturation curves were well fitted for relationships between leeward distance and U/U_o for both TL ($R^2 = 0.96$, $p = 0.009$) and QL ($R^2 = 0.95$, $p = 0.009$) sites (Fig. 3). The curves indicate that at 85 m leeward (8H) the wind speed recovers 70 % U_o for *C. equisetifolia* shelterbelt at TL site and it is 130 m (16.5H) for *A. auriculiformis* shelterbelt at QL site.

There was weak negative linear relationship ($R^2 = 0.44$, $p = 0.10$) between D_2 and U/U_o at QL site. But generally, the relationships were not existed for each site separately or for all sites combined (Fig. 4). The negative linear pattern was best fitted for relationship between D_3 and U/U_o at 5H leeward for each site separately (Fig. 5a, b, c) and for all sites combined (Fig. 5d) with moderate strength. The slope was greater at *A. auriculiformis* shelterbelt site (Fig. 5c) compared to *C. equisetifolia* shelterbelt sites (Fig. 5a, b), indicating the more wind reduction efficiency at QL site compared to other sites (TL and HA).

Discussion

Pre-surveyed indicated that there was no difference of windward speed at -5, -7, and -10H in the present study. The higher wind speed at -5H, the more reduction efficiency at 5H behind *A. auriculiformis* shelterbelt at QL site was found, but not for *C. equisetifolia* shelterbelts at other sites (Fig. 2). There probably are some reasons. Firstly, there was high variation of windward speed (0.4–5.1 m s^{-1}) at QL site located 2.5 km from the sea, while there were lower ranges and higher mean of windward speed at TL and HA sites (Table 1). Secondly, different species have different crown shape as *A. auriculiformis* with streamlined-triangulated shape (Wang and Takle 1997) and dense crown, while *C. equisetifolia* has triangulated shape and sparse crown. In addition, *A. auriculiformis* leaves have bladed-shape with the length of 10–20 cm and width of 3–7 cm, while *C. equisetifolia* leaves have needled-shape (toothlike leaves) with diameter less than 0.05 mm. Thirdly, void in shelterbelt (under crown height in shelterbelt) was also different among sites, which was 3.6 m at HA, 3.4 m at TL, and 1.5 m at QL

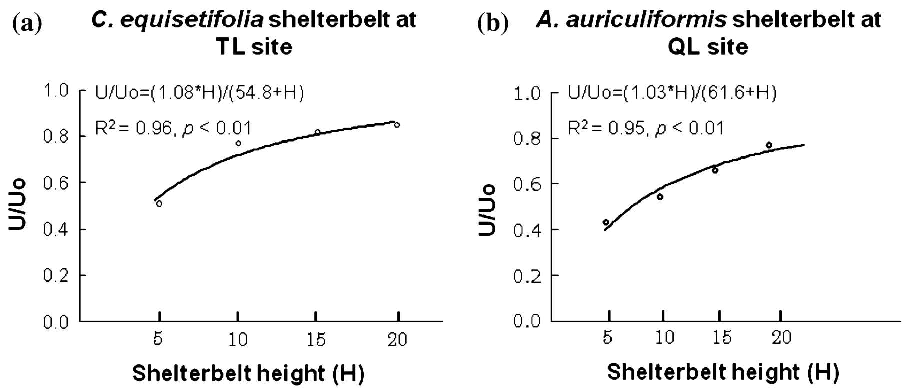

Fig. 3 Relationship between leeward distances and U/U_o

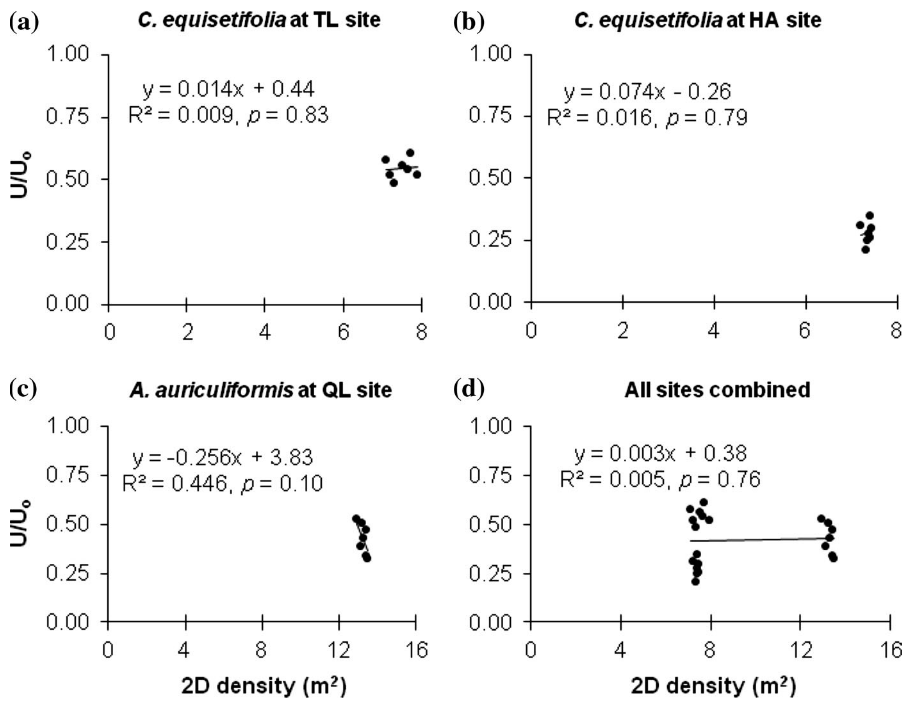

Fig. 4 Relationship between 2D density (D_2) and U/U_o at 5H leeward

(Table 1), may also respond for such different in reduction efficiency at 5H. Larger void (higher under crown height) allows higher ratio of wind penetrating through shelterbelt, leading to lower reduction efficiency at 5H. Such differences lead to lower wind speed penetrating through *A. auriculiformis* canopy compared to *C. equisetifolia* canopy at high windward speed. Similar results were also found in Nebraska, USA (Zhang et al. 1995a), where increase U_o from 1 to 5 m s^{-1} led to decrease of leeward speed at 5H from 70 to 20 %. Such decrease only happens when U_o is less than threshold wind speeds, which are different depending on species, width etc. of shelterbelt (Nageli 1965; Brown and Rosenberg 1972; Zhang et al. 1995a). Those indicate that 5H windward speed of maximum 6.8 m s^{-1} in the present study (Table 1) is less than threshold wind speed. In fact in coastal sandy land of Vietnam, *A. auriculiformis* shelterbelt has never been established close to the sea where there is high wind speed up to 10–12 m s^{-1} compared to further inland. *A. auriculiformis* cannot grow there because of salty humidity from the sea and too strong wind exceeding critical wind speed (Zhang et al. 1995b) leading to broken bladed-shape leaves of *A. auriculiformis* (Dang 2004).

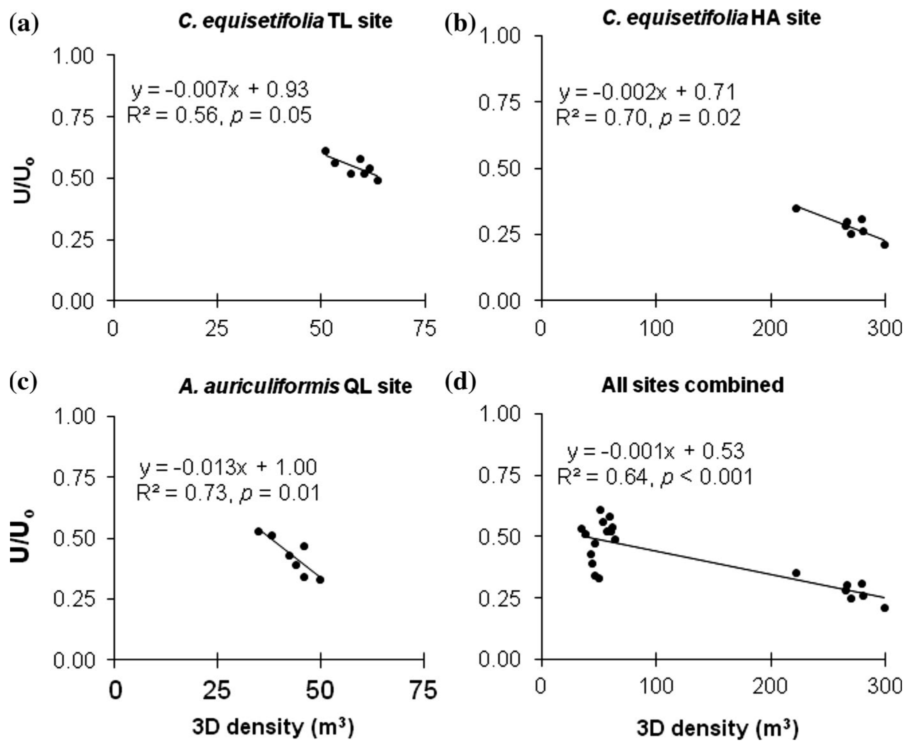

Fig. 5 Relationship between 3D density (D_3) and U/U_o at 5H leeward

Torita and Satou (2007) indicated the shelter distance (d70) which the leeward speed U does not exceed 70 % windward speed U_o to represent the wind reduction efficiency of shelterbelt. In the present study, d70 of *A. auriculiformis* shelterbelt is 130 m (16.5H) much further than that of *C. equisetifolia* shelterbelt (85 m; 8H; Fig. 3), even the former has shelterbelt width of 4 m compared to 26 m of the later. This finding in agreement with Nageli (1946), who indicated that a dense shelterbelt has a rapid wind speed recovery and shorter protection distance, compared to more porous shelterbelt (Zeng et al. 2010). Some other studies also indicated that very wide shelterbelts are less effective in wind reduction than narrow ones (Caborn 1957; Grunert et al. 1984). This may indicate that species selection for shelterbelt establishment is much important, which later will create different structure and shelterbelt porosity. Even higher wind reduction efficiency of *A. auriculiformis* shelterbelt compared to *C. equisetifolia* shelterbelt, considering suitable climate conditions is the first important step otherwise *A. auriculiformis* cannot grow well, for example close to the sea, and in turn reducing wind reduction efficiency.

The relationship between two-dimensional crown (2D) porosity and shelter effect is largely understood (Torita and Satou 2007). It is concluded that optical 2D porosity is closely related to the minimum leeward wind speed in narrow shelterbelts (Heisler and Dewalle 1988), where higher porosity led to lower wind speed reduction efficiency for shelterbelts of two planted rows with less than 8 m width (Zhang et al. 1995a). More or less the same conclusion was found in the present study for *A. auriculiformis* at QL site, which has shelterbelt width of 4 m. However, strength of negative linear relationship between U/U_o and 2D crown density was quite weak ($R^2 = 0.45$; Fig. 4c). For wider shelterbelts of *C. equisetifolia* at TL (26 m wide) and HA (90 m wide) sites, such relationship does not exist (Fig. 4a, b). Since 2D crown density/porosity does not well present for wide shelterbelts and is always less than the actual value (Lindholm et al. 1988).

Simple estimated three-dimensional crown (3D) density in the present study had a good relationship with U/U_o at 5H leeward (Fig. 5). Such negative linear indicated that shelterbelt with higher 3D density has higher wind reduction efficiency. Physically, 3D density defined as Eq. 1 represents volume covered by crown of planted trees in 1 m length shelterbelt. Generally, the wider shelterbelt with wider and longer crown shape of planted trees, which present both horizontal and vertical structure, results in higher 3D density. To get through shelterbelt, wind meets many obstacles as many layer of leaves, braches, and stems. Therefore, ratio of wind speed penetrating through shelterbelt is small. 3D density in the present study can be easily estimated based on shelterbelt parameters measured in the field compared to other porosities (Wang and Takle 1997; Santiago et al. 2007). However, comparing wind speed reduction efficiency between shelterbelts of the same and/or different planted species with the same height and width in the same study site for wider range of windward speed has not yet been done because of unavailability. Therefore, selecting species and designing shelterbelt to meet different objectives of landowners based on 3D density may be only applicable for these *A. auriculiformis* and *C. equisetifolia* species on a limit windward speed at −5H less than 7 m s^{-1}. It requires to be further examined for other species and wind speed range.

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