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SHELTER EFFICIENCY OF DOUBLE-ARRANGED WINDBREAKS

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Abstract

Experiments were carried out in an atmospheric boundary layer wind tunnel in order to understand better the fluid mechanical principle of double-arranged, mound-mounted shelterbelts. Such shelterbelts are often realized by rows of trees interacting with the atmospheric approach flow. The influence of the angle of mound as well as of the ratio of shelterbelt height to mound height on the flow characteristics in the intermediate field of two windbreaks arranged in parallel has been investigated. Results are given in form of contour plots and protection volumes. The shelter efficiency of the double-arrangements is compared to that of adequate single line windbreaks.

1. Introduction

The plantation of windbreaks and shelterbelts, designed to protect agricultural land, residential areas, traffic roads and industrial sites against wind attacks, requires the knowledge of aerodynamic characteristics of any particular shelter device. The design of a windbreak arrangement has to be adapted to the specific site conditions in order to obtain a maximum reduction of convective flow quantities in the protected area.

Windbreaks can be performed as artificial barriers or as belts of trees and/or shrubs (shelterbelts). Besides single lines of windbreaks, located at the windward side of an area, also windbreak systems were erected surrounding whole areas or industrial sites. Thus, in many cases the surrounded area can be conceived of as being protected by a windward and a leeward windbreak (double-arrangement).
The windbreak height is considered to be the main factor governing the effectiveness of windbreaks (e.g. Heisler and DeWalle 1988). In order to obtain an increased shelter, shelterbelts are often mounted on thrown-up earth walls (mounds).

The knowledge about the wind shelter efficiency of mound-mounted shelterbelts is limited to single-line belts (Ruck and Donat 2000, Ruck 2001). Therefore, the aerodynamic behavior in the intermediate field of double-arranged mound-mounted shelterbelts is within the scope of this research project reported here. Besides other factors of influence as e.g. distance between windbreaks and shelterbelt porosity (Frank and Ruck 2002, 2003), emphasis is laid in this paper on the influence of angle of mound and ratio of shelterbelt height to mound height. Fundamental findings and relations between the relevant windbreak structural parameters are given in order to define an optimum sheltering efficiency. The flow characteristics in the intermediate field were investigated in a systematic experimental study conducted in an atmospheric boundary layer wind tunnel. Differently defined wind protection parameters were deduced from the measurements. The shelter efficiency of the investigated double-arranged windbreak systems is compared to the efficiency of single-line windbreaks.

2. Experimental methods

The experiments were performed in the closed-circuit atmospheric boundary layer wind tunnel at the Institute of Hydromechanics / University of Karlsruhe. The lower part of a neutrally stratified atmospheric boundary layer was simulated, which is typical for suburban terrain and forested areas, respectively. The measurements of the flow quantities were accomplished with the aid of a two-component laser Doppler anemometer system (LDA).

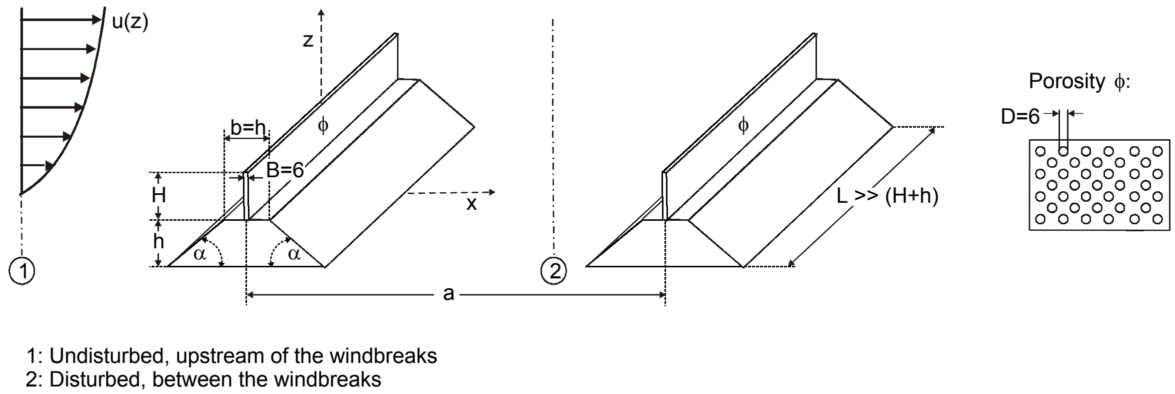

Fig. 1: Sketch of the windbreak models and nomenclature used.

The windbreak models and coordinate system are sketched in Fig. 1. The overall height h+H of a windbreak (h = height of mound and H = height of shelterbelt) amounted to 120 mm. In order to achieve two-dimensionality of the center-lined flow, the length L of the windbreak models extended over the entire width of the test section. The approach flow was set perpendicular to the windbreak length. More detailed information on the experimental set-up is given in Frank and Ruck 2002, 2003.

Three different angles of mound α (α = 20°, 40° and 60°) were investigated. For each angle, six varied distances a between the windbreaks ranging from 5 to 20 times the windbreak height (h+H) were investigated. The ratio of shelterbelt height to mound height H/h = 1 and the shelterbelt porosity ϕ = 22 % were kept constant. In addition, impermeable shelterbelts (ϕ = 0 %) and medium-dense shelterbelts (ϕ = 52 %) were tested for a distance between the windbreaks of a = 10·(h+H).
Furthermore, five different ratios of shelterbelt height H to mound height h were investigated: H/h = ∞ (shelterbelt without mound), 2, 1, 0.5 and 0 (only mound). Thereby, the distance a between the windbreaks was modified four times in the same range as mentioned above for the windbreak arrangement α = 40° and ϕ = 0 % (impermeable windbreak).

3. Results

In this paper, the effectiveness of a windbreak system is assessed with the aid of a protection parameter S_u. S_u is suitable to assess the reduction of mean wind velocities and related aerodynamic wind forces on bodies in the intermediate field of two windbreaks:

$$S_u(x,z) = 1 - \frac{u_2(x,z)^2}{u_1(z)^2}$$

This parameter refers (at a height z) the local horizontal momentum fluxes of the disturbed (sheltered “2”) flow field to the momentum fluxes of the undisturbed (unsheltered “1”) flow field in the approach flow. Since the aerodynamic force exerted on bodies is proportional to u^2, the protection factor S_u indicates also the percentage of wind force reduction. If $S_u > 0$, the impact of wind forces decreases; if $S_u < 0$, it increases. The wind turbulence (gustiness) is explicitly not considered with this specific protection parameter.
Using this parameter, protection volumes could be calculated. A protection volume was defined as an area in the intermediate field of two windbreaks, in which S_u amounts to at least a pre-defined value, multiplied by the length L of the windbreak (the extent perpendicular to the approach flow direction).

Further protection parameters, considering the change of momentum exchange in vertical direction and of pedestrian comfort conditions, were introduced in Frank and Ruck 2003 and can be calculated in a similar manner from the measurement results.

3.1 Influence of angle of mound α on the wind shelter effect

Contour plots of the protected areas in the intermediate field of two windbreaks with different angles of mound α are shown in Fig. 2 with varying protection parameter S_u (S_u = 0.25, 0.5 and 0.75) exemplary for a distance between windbreaks of a = 15·(h+H). The sizes of the protection volumes are also given as normalized values v’. In Fig. 3 the sizes of protection volumes are shown as a function of distance a between the windbreaks with varying angle of mound α for low and high shelter (S_u = 0.25 and S_u = 0.75, respectively).
It can be seen in these figures that the angle of mound affects only slightly the shelter efficiency of double-arranged windbreaks. The protection volumes v´ of windbreak arrangements with angle of mounds α = 40° and α = 60° are very similar. Taking into account all investigated distances a and all protection parameters S_u in the range between 0.2 and 0.8, the mean decrease of v´(α = 60°) amounts to 1 % of v´(α = 40°). However, windbreak configurations with the steeper mounds do not always cause smaller protected areas than those with α = 40°.

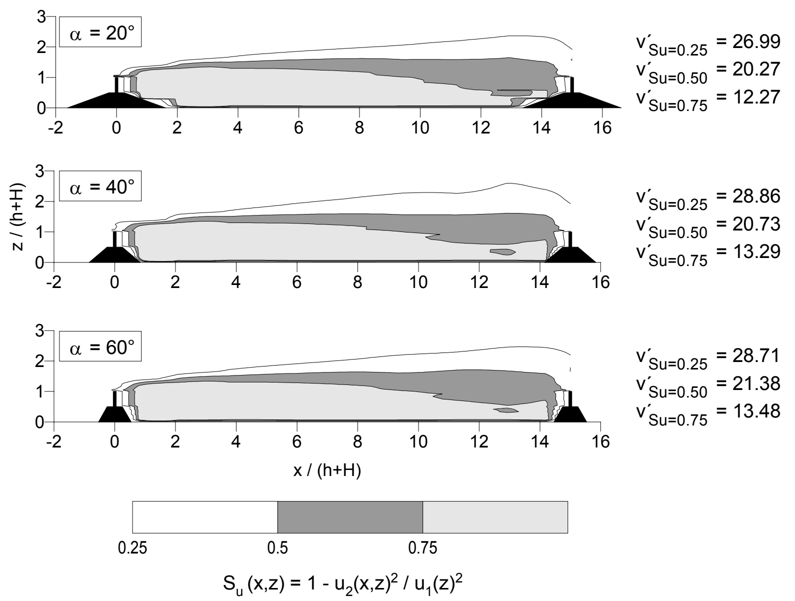

Fig. 2: Contour lines of the protection parameter S_u as a function of angle of mound α and corresponding protection volumes $v'_{Su} = V_{Su} / ((h+H)^2 \cdot L)$. (a = 15·(h+H), ϕ = 22 %, H/h = 1).

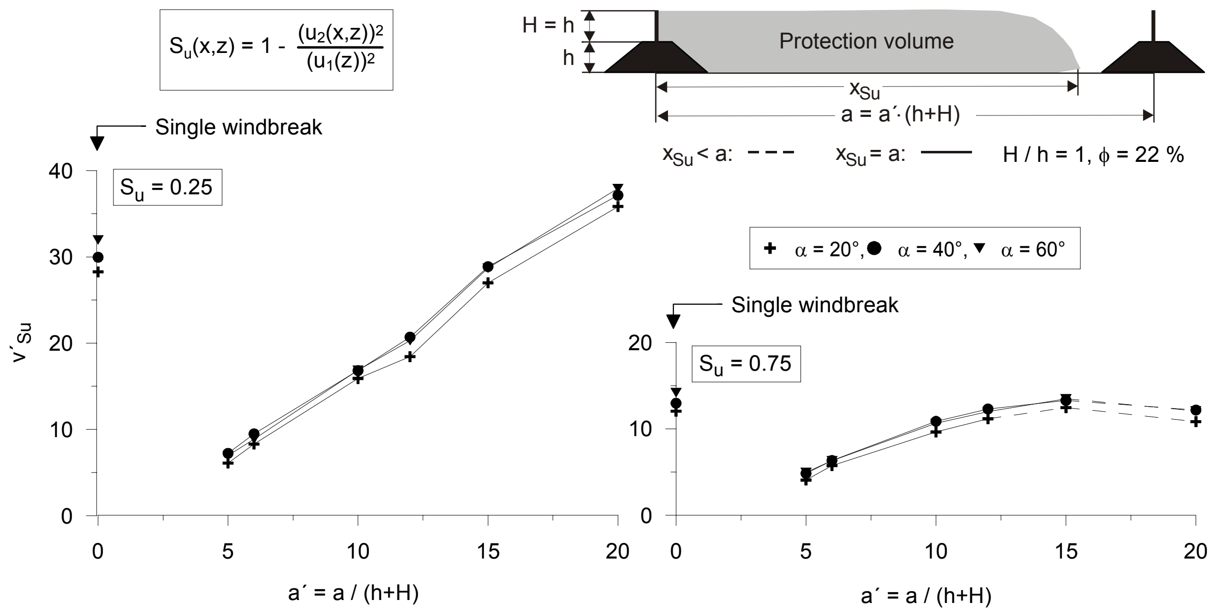

Fig. 3: Protection volumes $v'_{Su} = V_{Su} / ((h+H)^2 \cdot L$ as a function of distance a between windbreaks with varying angle of mound α. (S_u = 0.25 and S_u = 0.75, ϕ = 22 %, H/h = 1).

Furthermore the figures show that windbreak arrangements with shallow mounds (α = 20°) cause always somewhat smaller protection volumes. Their sizes average 9.8 % less than those of arrangements with α = 40°.
The comparison of the protection volumes in the intermediate field of double-arranged windbreak-systems with those leeward of adequate single-line windbreaks (Ruck and Donat 2000, Ruck 2001) reveals a similar behavior (Fig. 3).

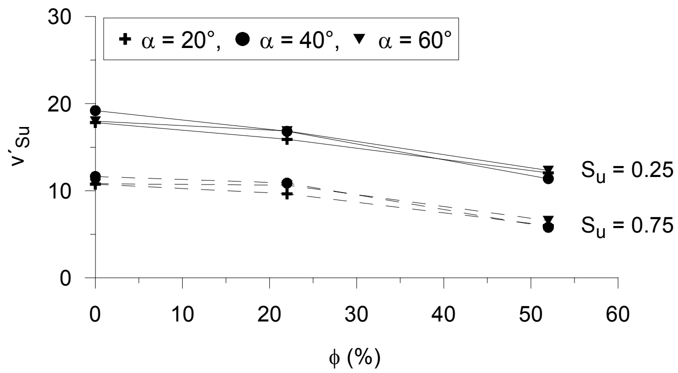

Fig. 4: Protection volumes $v'_{Su} = V_{Su} / ((h+H)^2 \cdot L$ as a function of porosity ϕ with varying angle of mound α. (S_u = 0.25 and S_u = 0.75, a = 10·(h+H), H/h = 1).

Regarding varied porous shelterbelts the influence of the angle of mound α on the size of protection volume v'_{Su} levels off (see Fig. 4, the difference between the curves is nearly constant). However, the aforementioned tendency that windbreak-arrangements with α = 20° cause smaller protection volumes than those with angles α = 40° and α = 60° cannot be observed at medium porous shelterbelts (ϕ = 52 %). In this case, the protected areas are the smallest in the intermediate field of the windbreak system with α = 40°, but the difference in size is very small and it cannot be excluded that it occurs due to a measurement inaccuracy.

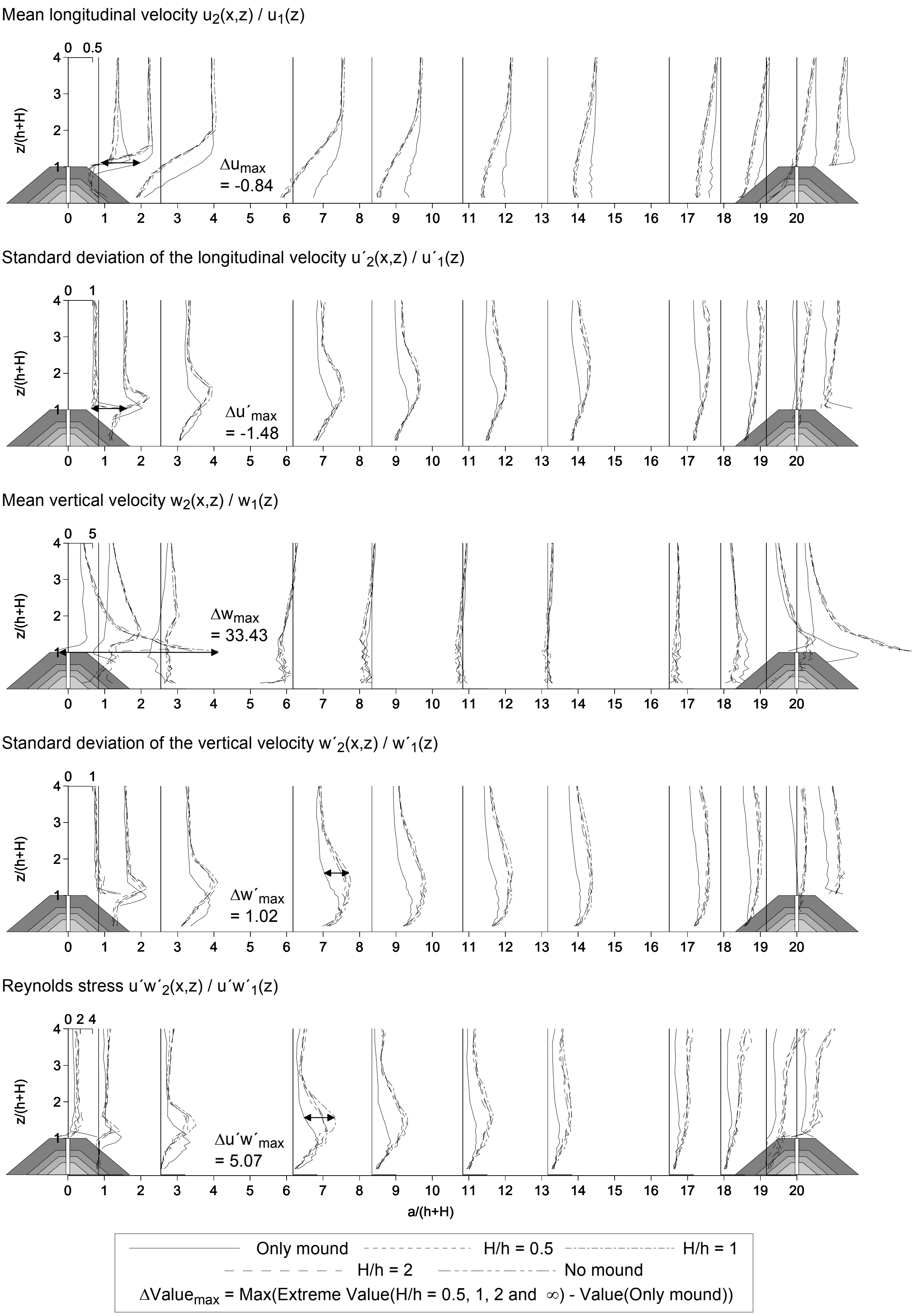

Fig. 5: Vertical profiles of the measured quantities in the intermediate field of two windbreaks ($a = 20\cdot(h+H)$, $\phi = 0$ %, $\alpha = 40°$) with varying ratio of shelterbelt height to mound height H/h.

3.2 Ratio of shelterbelt height to mound height H/h

3.2.1 Velocity and standard deviation profiles

Vertical profiles of measured flow quantities are shown in Fig. 5 for windbreak configurations with varying ratio of shelterbelt height to mound height H/h for a distance between two windbreaks of a = 20·(h+H). Mean velocities, standard deviations and Reynolds stresses were measured in both the longitudinal and the vertical direction. They were normalized with the profiles of the corresponding quantities in the undisturbed (unsheltered) approach flow.
The profiles in the intermediate field of impermeable mound-mounted shelterbelts and of shelterbelts without mound show only small differences. In contrast to that, the profiles for the mound without shelterbelt (but same height) differ significantly from those of the other arrangements: Whereas the longitudinal velocities increase, the standard deviations of both directions as well as the Reynolds stresses decrease. The latter applies not for the area in the near lee of the first windbreak where an increase of the turbulent quantities can be observed.

3.2.2 Protection parameter S_u

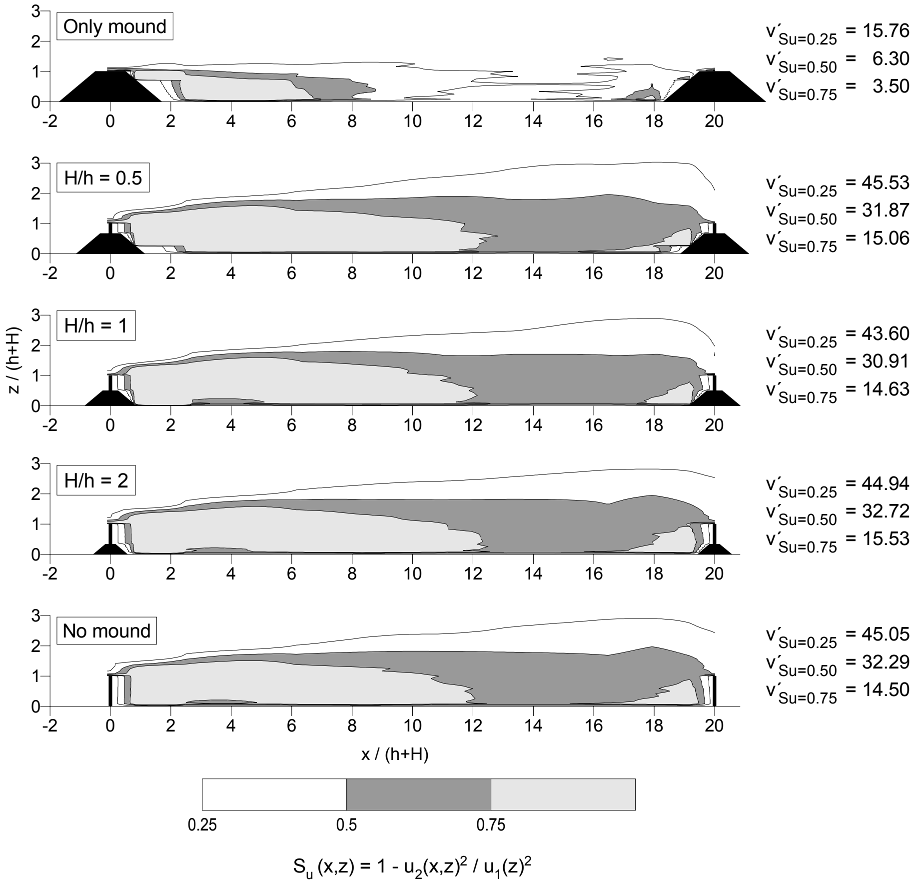

Fig. 6: Contour lines of the protection parameter S_u as a function of ratio of shelterbelt height to mound height H/h and corresponding protection volumes $v'_{Su} = V_{Su} / ((h+H)^2 \cdot L)$.
(a = 20·(h+H), ϕ = 0 %, α = 40°).

For a distance between windbreaks of a = 20·(h+H), contour lines of three different protection parameters S_u (S_u = 0.25, 0.5 and 0.75) are shown in Fig. 6 (with varying ratio of shelterbelt height to mound height H/h). Additionally, the sizes of the depicted protected areas v´ are given again. In Fig. 7 the sizes of protection volumes are shown as a function of distance a between windbreaks with varying ratio of shelterbelt height to mound height H/h for low and high shelter (S_u = 0.25 and S_u = 0.75, respectively). It can be seen that the protection volumes between impermeable mound-mounted shelterbelts and between impermeable shelterbelts without mound are very similar in shape (Fig. 6) and size (Fig. 7). The difference in size of these protection volumes $\Delta v' = v'_{Max} - v'_{Min}$ varies solely between 0.24 and 2.51 (Fig. 8a). The mean absolute deviation amounts to 1.21. As can be seen in Fig. 8b, this corresponds to a decrease of size $\Delta v'$ between 1.4 % and 16.0 %, with respect to the maximum protection volume. Thereby, the mean deviation amounts to 7.9 %.

However, the protection volumes between mounds without shelterbelts differ considerably from those of the other arrangements. The difference in size of the protection volumes $\Delta v' = v'_{Only\ Mound} - v'_{Max}$ increases with increasing distance and with decreasing protection parameter S_u (Fig. 8c). The mean deviation amounts to -12.39. Thereby, the protection volumes in the intermediate field between two mounds are smaller of around 42.9 % up to 81.5 %, with respect to the maximum protection volume, than those of the most effective windbreak-arrangement (Fig. 8d). The mean decrease amounts to -63.2 %.

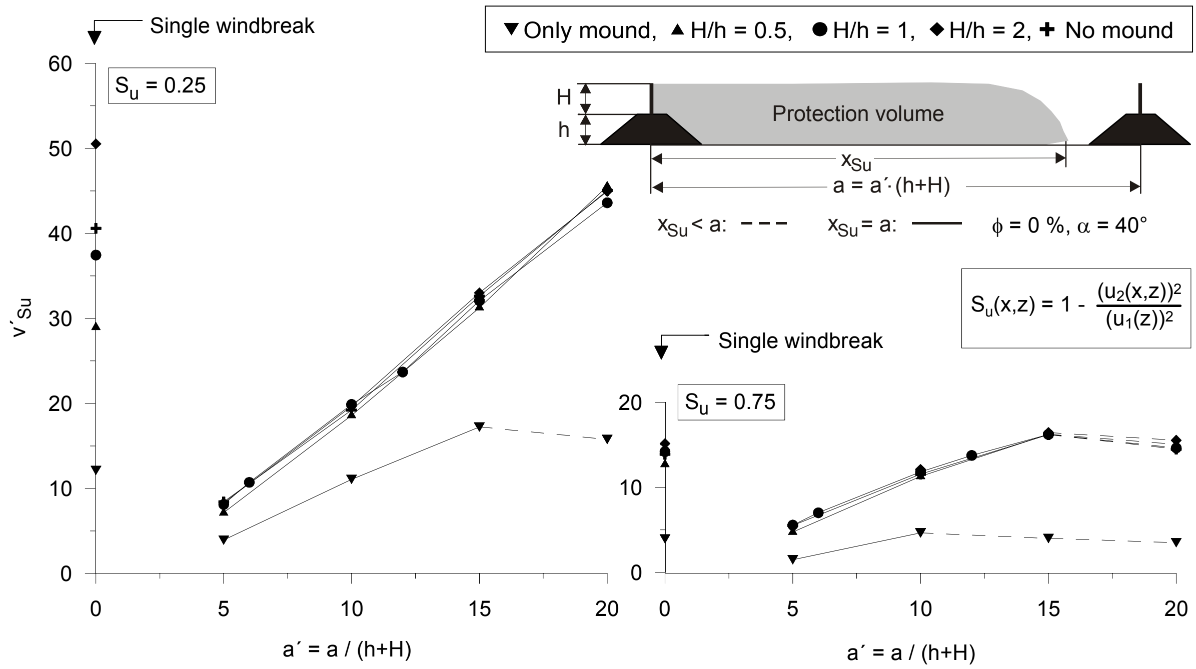

Fig. 7: Protection volumes $v'_{Su} = V_{Su} / ((h+H)^2 \cdot L$ as a function of distance a between windbreaks with varying ratio of shelterbelt height to mound height H/h.
(S_u = 0.25 and S_u = 0.75, ϕ = 0 %, α = 40°).

A comparison of the shelter effect of double-arranged windbreaks with that downstream of single-line windbreaks (Ruck and Donat 2000, Ruck 2001) shows deviations especially for low shelter efficiency (Fig. 7, S_u = 0.25). Apart from the case of mound without shelterbelt, a significant influence of the ratio of shelterbelt height to mound height H/h on the size of the protection volumes v'_{Su} cannot be observed with the investigated double-arranged windbreaks. Furthermore, the result that single-line windbreaks with H/h = 2 cause the largest protection volumes v'_{Su} cannot be confirmed for each investigated double-arrangement.

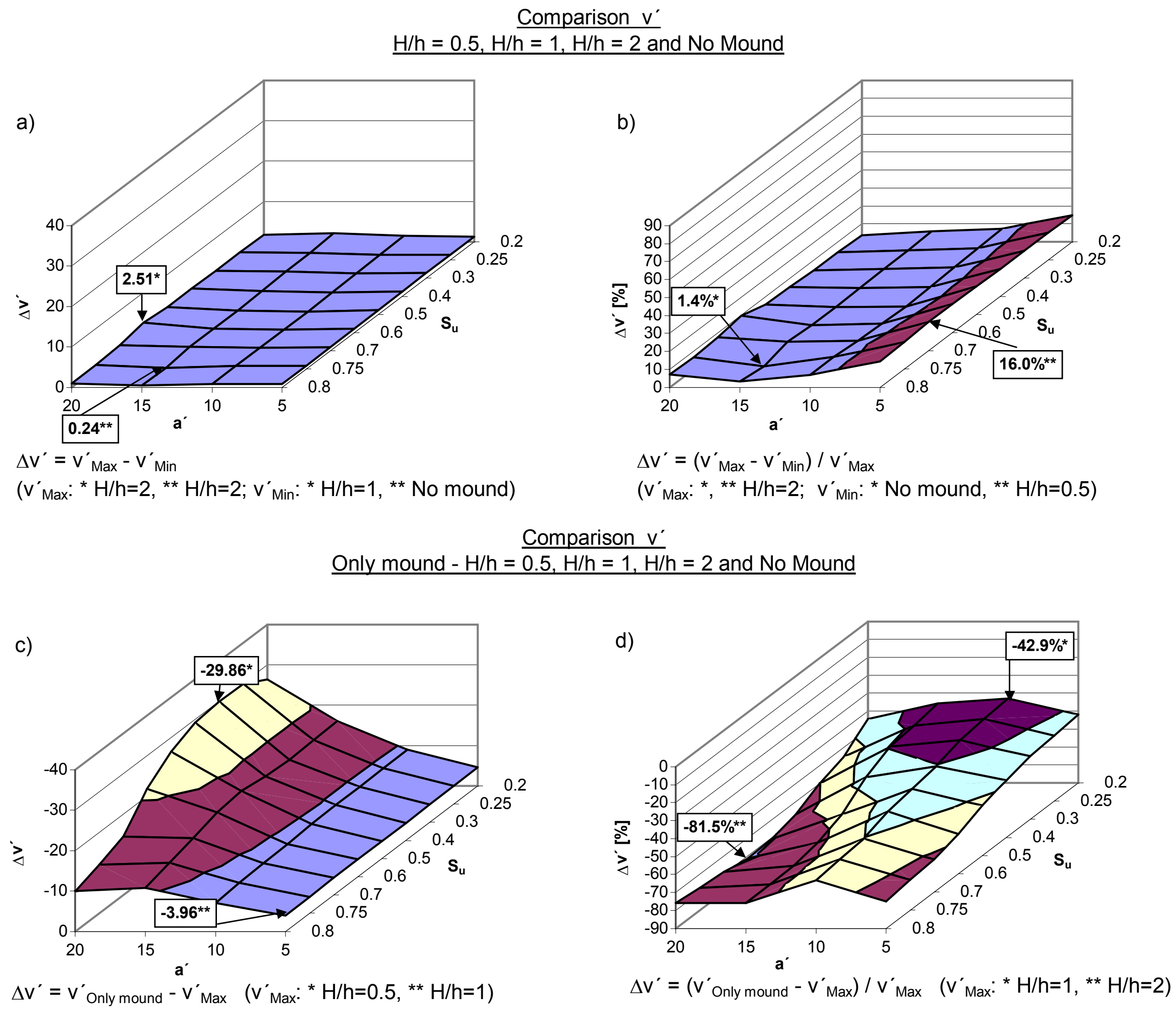

Fig. 8: Differences in size of protection volumes $v'_{Su} = V_{Su} / ((h+H)^2 \cdot L$ as a function of distance a between windbreaks and of protection parameter S_u. (ϕ = 0 %, α = 40°).

Acknowledgements

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