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WIND TUNNEL STUDIES OF WINDWARD EDGE STRUCTURE ON THE FLOW WITHIN AND ABOVE FOREST REGION

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Abstract. *In this work wind tunnel experiments were carried out to study the influence of windward edge structure on the flow pattern within and above an idealized eucalyptus stand. Four different types of tree edge architectures were used in a wind tunnel atmospheric boundary layer wind tunnel. The wind velocity vertical profile was measured with a Pitot tube within and above the model eucalyptus forest. The objective was to identify a configuration that would reduce the wind speed in the trunk space of the eucalyptus stand. Among the four windward edge structures tested, two showed efficient wind reduction within the eucalyptus stand. This can be explained by the wind flow retardation due to blockage effect of the dense tree structures.*

Keywords: *forest flow; wind tunnel; tree structure, eucalyptus; blockage effect.*

1. INTRODUCTION

Wind damage is a major disturbance that can greatly affect both structure and function in both natural and managed forests (Franklin *et al*., 2002; Zeng *et al*., 2007). The interaction between wind field (i.e. wind speed, duration and gustiness) and trees can result in substantial economic losses in forests (Gardiner and Quine, 2000; Peltola, 2006). The susceptibility of trees to wind damage depends on several parameters such as: tree species, height, diameter, crown area, rooting depth and width, as well as, stand density, forest edge structure, canopy roughness (Peltola *et al.* 2000; Zeng *et al*., 2009) and characteristics of the site such as the topography and soil type (Boose *et al*., 1994).

In a managed forest the economic losses due wind damage increase costs because of unscheduled thinning and clear-cutting, in that way reducing the profitability of a forest managed for timber production and also thereby resulting in forest planning problems. Furthermore, broken and uprooted trees left in the forest can lead to detrimental insect attacks on the remaining trees because of the increased availability of breeding material (Zeng *et al*., 2009).

A number of works for predicting the interaction, wind-forest systems, have been developed. However, accurate prediction of wind damage is difficult due to the complex structure of wind flow within and above forest regions and the complexity in array of forest elements (Hassinen *et al*., 1998). Studies of the response of trees to wind load have used dynamic models. Peltola *et al*. (1999) and Gardiner *et al*. (2000) have independently developed two mechanistic models, HWIND and GALES, respectively, used to predict, for a given tree, the critical wind speed needed for breakage of the branches or uprooting. However, Schelhass *et al*. (2007) has pointed out several problems in these models, presumably because they only evaluate the stability of an individual tree and ignore the interactions among the trees.

Ancelin *et al*. (2004) developed FOREOLE, an individual-based mechanical model of tree response to wind speed for the characterization of the distribution of damage in a population of trees for a given wind event. The authors related that the HWIND and GALES model are well adapted to regular stands, but in heterogeneous stands, not all the trees are necessarily damaged at the same time.

On the other hand, several studies have shown that trees along a forest margin, downstream of large clear-cut area or large area of open land experience heavy wind load and therefore are at high risk for wind damage (Talkkari *et al*., 2000). Yang *et al*. (2006) investigated the wind load on trees, quantified by wind moment at a forest edge, by employing a large eddy simulation (LES). The purpose of study was to enrich understanding of the risk of wind-induced tree damage downwind of a forest edge.

Dupont and Brunet (2008) carried out studies concerning the influence of forest edge structure (sharp, tapered, sparse, dense, tall and small edges) to investigate tree vulnerability to wind load. A LES flow model was used to compute mean and extreme tree bending moments. Tree vulnerability was slightly reduced downwind from tapered, sparse and small edges and enhanced downwind from dense ones. The gust factor (i.e. the ratio of tree bending moments) was reduced in the edge region, however increased further downstream due to the interaction of the canopy with the wake of the edge treatment.

Seeking to understand the mechanism of wind-induced damage in forests, the behavior of trees under wind loading has been studied in wind tunnel experiments (Gardiner *et al*., 2005; Vollsinger *et al*., 2005). These experiments are important to study how evaluated an alternative response to wind damage for the reduction of the windthrow. One

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method that can be adopted is to windbreak with shelterwood, an approach which can be used to reduce wind speed and alter wind fields. The shelterwood structure has an influence on the aerodynamic wind velocity and turbulence stress (Wilson, 1987). The upwind tree structure can provide a shelter effect for the downwind stand due to its effects on the surface roughness (and wind profile) and may result in lower wind loading at the downwind stand (Zeng *et al*., 2007; Zeng *et al*., 2009). The present study is concerned with identifying an upwind tree structure that provides a shelter effect and reduced wind speed for a downwind eucalyptus forest. These studies were conducted within and above a forest region immersed in an atmospheric boundary layer wind tunnel.

2. MATERIAL AND METHODS

2.1 Wind tunnel experiments

In this work, atmospheric boundary layer wind tunnel, model trees and Pitot tube were used to investigate the mean wind velocity. The wind tunnel is an open-return blow-through tunnel, 2.0 m long by 0.5 m high and 0.5 m deep. Turbulent flow simulating the atmospheric boundary layer in neutral-stability conditions was generated by a combination of wood spires (0.35 m high) and roughness elements (cubical wooden blocks of 0.035 m) placed successively downwind from the inlet for a total length of about 2.0 m. Immediately downwind of these was a 1.5 m long section of model forest.

Orthogonal wind-tunnel coordinates (x,y,z) were defined as being along the wind tunnel main axis and increasing downstream. At $x = 0$ (longitudinal flow), corresponding to the upstream edge of the model forest, at $y = 0$ (lateral flow) corresponding to the centre of the wind tunnel, this axis is to horizontal and perpendicular to the x-axis, and at $z = 0$ (vertical flow) corresponding to the wind tunnel floor, perpendicular to the x-y plane and increasing upwards.

Flow velocities in the vertical direction were measured using a Pitot probe and micromanometer (TSI Model EBT 720). The Pitot probe was positioned at $x = -1.0\ h$; $2.0\ h$; $4.0\ h$ and $6.0\ h$, (where h is forest height) within and above the forest model. All profiles consisted of 30 measurements at $z = 0.01$; 0.03; 0.05, … , 0.37 m and $z/h = 1$(the top of the forest). The Reynolds number for the oncoming flow corresponded to 81600. The Reynolds numbers were based on forest height $h = 0.215$ m and free stream velocity at the forest height, $U_h = 6{,}1$ m/s. Figure 1 shows a sketch of the wind tunnel test section, measurement system and homogeneous forest localization.

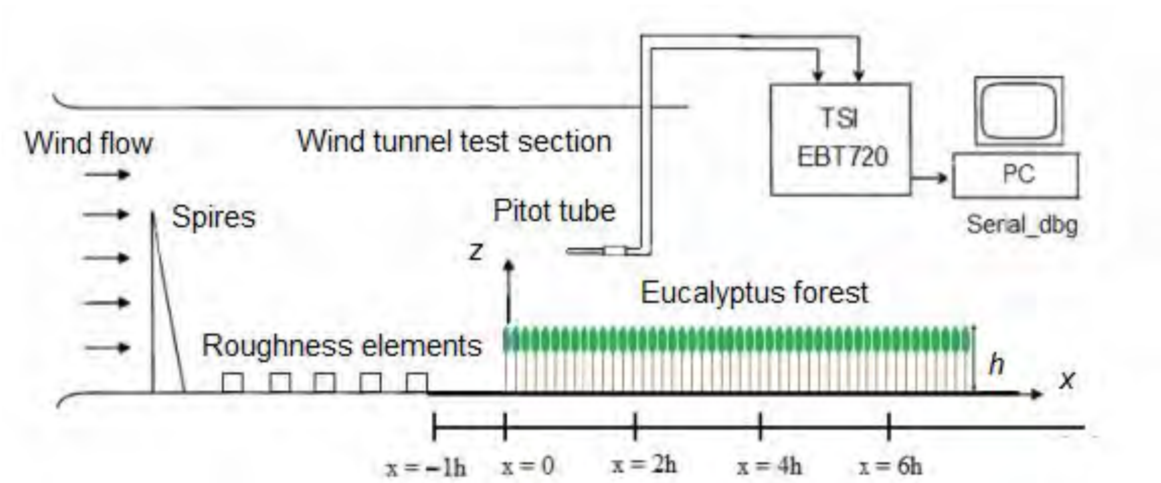

Figure 1. Sketch of the wind tunnel test section, measurement system and homogeneous forest localization.

2.2 – Forest model and tree upwind edge structure

The first scale model forest one with a homogeneous canopy, which was designated WTF1 (wind tunnel forest 1). The scale model forest was placed behind the roughness elements, at $x = -1.0h$, extending 1.5 m downstream and spanning the test section. It consisted of scale models of eucalyptus trees, on average 0.215 m high, crown average diameter of 0.06 m, crown height of 0.07 m and with a trunk of 2.0 mm diameter iron rod. The trees were mounted in an interlock pattern with a density of 1086 trunks m^{-2} and 0.03×0.03 tree spacing.

In this study, different windbreaks formed by different tree structures upstream from the homogeneous eucalyptus forest were tested, these trees were designated: T1 (tree type 1); T2 (tree type 2); T3 (tree type 3); T4 (tree type 4). Table 1 presents the geometric configuration of trees. Table 2 shows the physical properties of the different edge structures, which were designated: WTF2 (wind tunnel forest 2); WTF3 (wind tunnel forest 3); WTF4 (wind tunnel forest 4); and WTF5 (wind tunnel forest 5).

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Table 1. Geometric description of the tree types used as shelterwood structure.

Tree type	Height of the trees (m)	Crown size of trees (m)	Crown Diameter (m)
TYPE 1(T1)	0.215	0.07	0.0250
TYPE 2 (T2)	0.220	0.09	0.0300
TYPE 3 (T3)	0.250	0.10	0.0400
TYPE 4 (T4)	0.190	0.15	0.0450
TYPE 5 (T5)	0.210	0.12	0.0325

Table 2. Physical description of the forest models.

Models	Tree Type	Number of the trees	Tree Spacing	Tree density	L_s (a)	λ_f (b)
WTF1	T1	750	0.03× 0.03	1086.9	1.5	0.33
WTF2	T2 and T1	525	0.03× 0.03	1111.1	0.27	0.41
WTF3	T3 and T1	525	0.03× 0.03	1063.8	0.285	0.40
WTF4	T4 and T1	525	0.05× 0.05	816.9	0.3	0.79
WTF5	T2; T2 and T1	675	0.03× 0.03	1102.9	0.55	0.57

(a) L_s is the length of windward edge structures
(b) λ_f frontal area index

3. RESULTS AND DISCUSSIONS

In this work wind tunnel experiments with forest scale models were analyzed to identify a tree structure that provided a shelter effect and reduced the wind speed for a downwind eucalyptus forest.

3.1 Homogeneous eucalyptus forest

Figure 2 shows the normalized of the mean wind vertical profile (U_m/U_h). The mean wind velocities, U_m, have been normalized with the mean wind velocity at the forest height, U_h, and heights, z, have been normalized with the height of the canopy (h = 0.215 m). The vertical velocity profiles were shown at three positions: within and above forest region (x = 2.0h; 4.0h; 6.0h). However, all data presented are averages of these vertical velocity profiles with equal weighting. Figure 3 shows a sketch of the side view of the homogeneous forest (WTF1) and measured points.

The flow field simulated in the wind tunnel presented low velocities within the forest (z/h <1) which shows an extraction of momentum by the trees; the mean wind vertical profile was characterized by an inflection point near the top of the forest (z/h = 1) due to a strong wind shear, see Fig. 2. The wind velocity profile was logarithmic above the tree tops (z/h > 1), which was evidence that the shear stress was decreasing in the observed logarithmic region. The mean velocity profile suggested an equilibrium state at x/h between 2.0 and 4.0. These experimental results were consistent with those which were reported in the literature by Raupach *et al.* (1996).

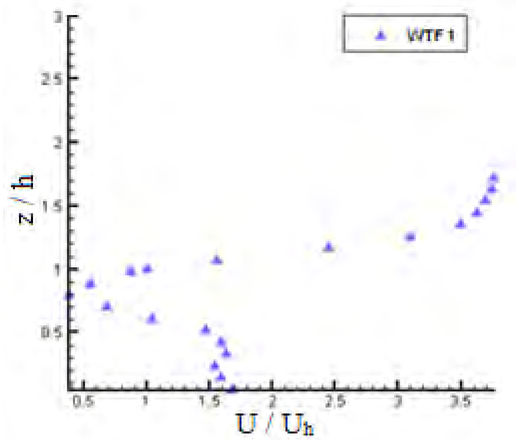

Figure 2 – Averaged vertical profiles of the normalized mean horizontal wind speed within and above WTF1.

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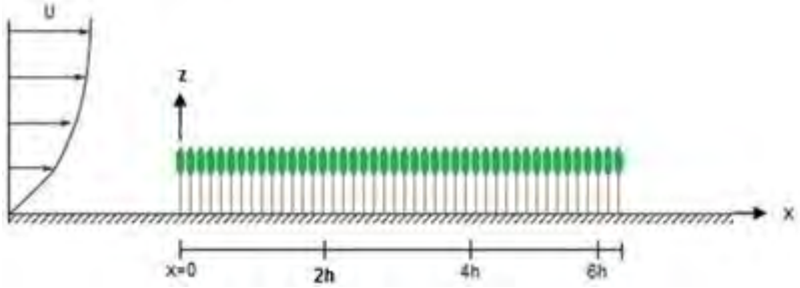

Figure 3. Side view: Schematic representation of the homogeneous eucalyptus forest (WTF1) and measurement points.

3.2 Forest with shelterwood upwind

Figure 4 shows the vertical profiles of the normalized mean wind velocity at the WTF2, the shelterwood upwind was formed with trees type T2. The velocity profiles were measured at two positions: within and above forest region occupied by type 1 trees (x = 2.0h and 6.0h). All data presented are averages of these velocity vertical profile with equal weighting. These results were compared against average profiles obtained within and above WTF1. Figure 5 shows a side view sketch of the forest (WTF2) and measurement points. The results showed that wind speed decreased slightly at $0.0 < z/h < 1.0$ due to the effect of the windward edge structure on the flow characteristics in the region occupied by T1 trees. With increasing height the mean wind velocity above the canopy top was lower with a windward edge structure in comparison with the mean wind velocity measured at WTF1.

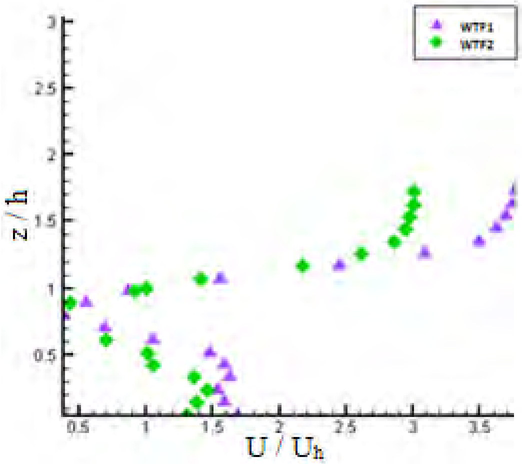

Figure 4 – Comparison of the averaged vertical profiles of normalized mean horizontal wind speed within and above WTF1 and WTF2.

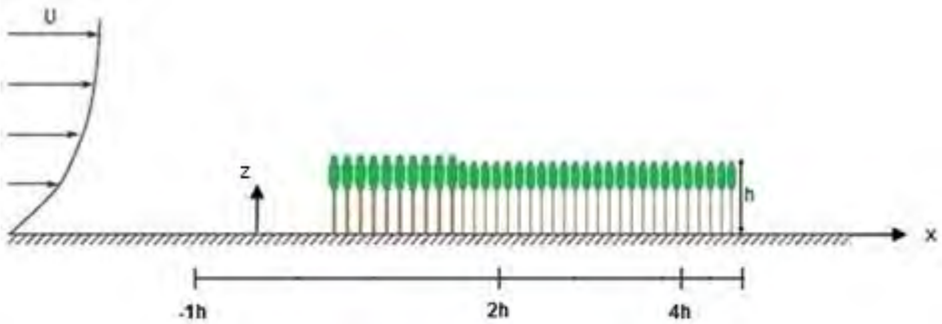

Figure 5. Side view: Schematic representation of WTF2: windward structure formed with trees type T2.

Figure 6 shows the normalized mean velocity vertical profiles at WTF3, the upwind shelterwood structure was formed with trees type T3 (tall trees). The velocity profiles were measured at two positions: within and above the forest region occupied by type 1 trees (x = 2.0h and 6.0h). All data presented are averages of these vertical profiles with equal weighting. These results were compared against average profiles obtained within and above WTF1. Figure 7 shows a side view sketch of the forest (WTF3) and measurement points. The results showed that wind speed increased at $0.0 < z/h < 1.0$ due to the effect of the windward edge structure on the flow characteristics in the region occupied by T1 trees. A possible explanation of these results is that the crown area of trees of type 3 was located at the same height as the crowns of the T1 trees and therefore not protecting the trunk space below.

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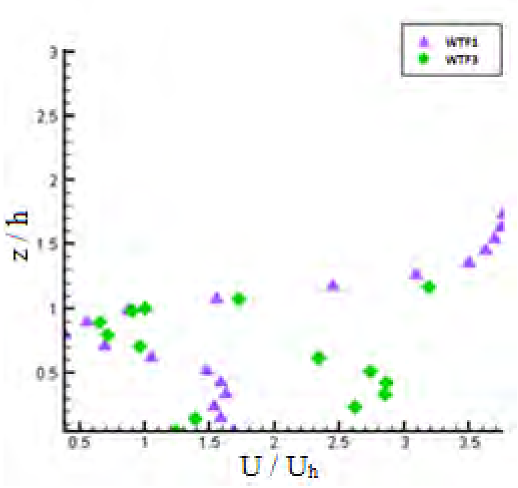

Figure 6. Comparison of the averaged vertical profiles of normalized mean horizontal wind speed within and above WTF1 and WTF3.

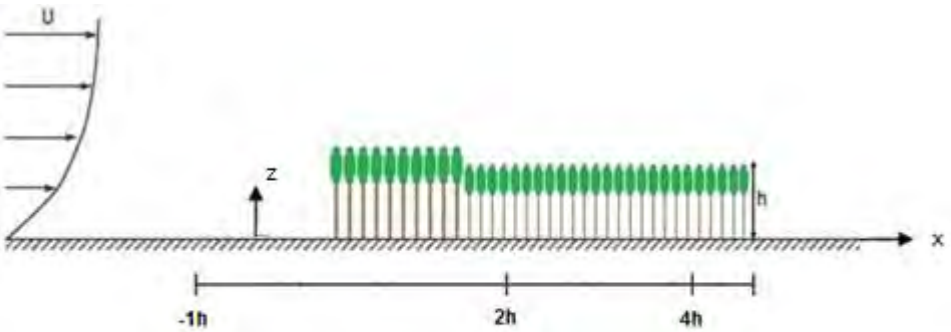

Figure 7. Side view: Schematic representation of WTF3: windward structure formed with trees type T3.

Figures 8 shows the normalized mean velocity profiles at WTF4, the dense shelterwood upwind was formed with trees type T4. The velocity vertical profiles were measured at two positions: within and above forest region occupied by type 1 trees (x = 2.0h and 6.0h). All data presented are averages of these vertical profiles with equal weighting. These results were compared against average profiles obtained within and above the WTF1. Figure 9 shows a side view sketch of the forest (WTF4) and measurement points. The results showed that wind speed decreased well at $0.0 < z/h < 1.0$ due to the effect of the windward edge structure on the flow characteristics in the region occupied by T1 trees. With increasing height the mean wind velocity above the canopy top was lower with windward edge structure when compared with the mean wind velocity measured at WTF1. In this case, a possible explanation of these results is that the crown of the type 4 trees was located in front the trunk space of the T1trees and gave a good shelter effect in the region occupied by them.

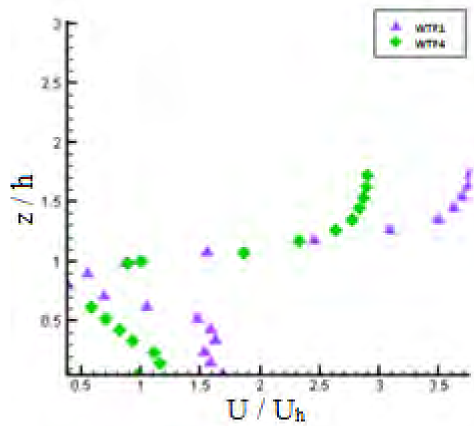

Figure 8 – Comparison of the averaged vertical profiles of normalized mean horizontal wind speed within and above WTF1 and WTF4.

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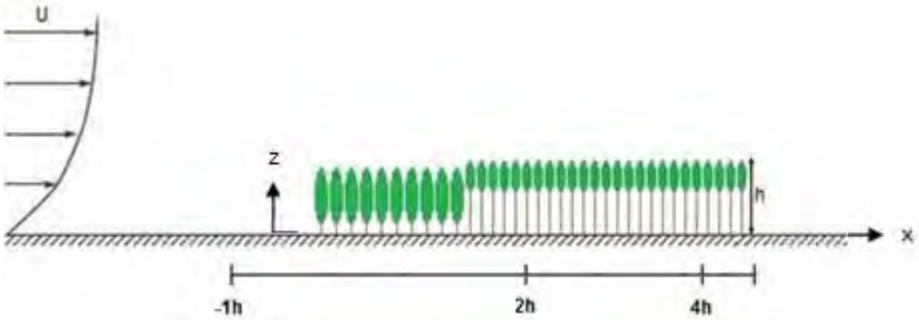

Figure 9. Side view: Schematic representation of the WTF4: windward structure formed with trees types T4.

Figure 10 shows the normalized mean velocity vertical profiles at WTF5. Two different types of trees were used in the windward edge structures: T2 and T4, with the same spacing. The velocity profiles were measure at two positions: within and above forest region occupied by type 1 trees (x = 2.0h and 6.0h). All data presented are averages of these vertical profiles with equal weighting. These results were compared against average profiles obtained within and above WTF1. Figure 11 shows a side view sketch of the forest (WTF5) and the measurement points. The results showed that the wind speed decreased well at $0.0 < z/h < 1.0$ due to the effect of the windward edge structure on the flow characteristics in the region occupied by T1 trees. With increasing height the mean wind velocity above the canopy top was lower with windward edge structure when compared with the mean wind velocity measured at WTF1. In this case, a possible explanation of these results is that the crown of trees of type 4 was located in front of the trunk space of the T1 trees, and caused a good shelter effect in the region occupied by the T1 trees.

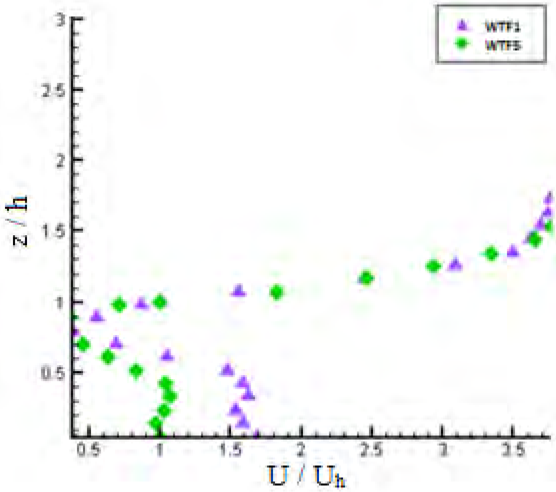

Figure 10 – Comparison of the averaged vertical profiles of normalized mean horizontal wind speed within and above WTF1 and WTF5.

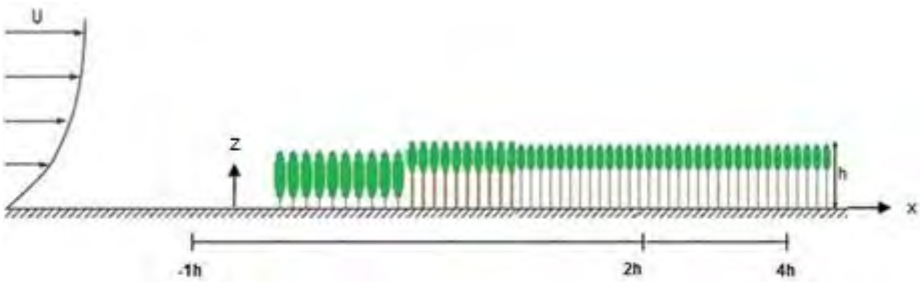

Figure 11. Side view: Schematic representation of WTF5: windward structure formed with trees types T2 and T4.

Table 4 shows the performance of the shelterwood structures for reducing the wind velocity in the region occupied by type 1 trees. Of the four windward edge structures used in this study WTF3, WTF4 and WTF5 showed a reduction of wind velocity within and above this region of the T1 trees. These results suggested that the shelter effect of upwind shelterwood was more effective for WTF3 and WTF5.

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Table 3. Performance (%) of the shelterwood structure for reducing the wind velocity.

Average height	WTF 2	WTF3	WTF4	WTF5
0.01 < z < 0.05	-8.17	-37.75	-5.92	-30.70
0.07 < z < 0.11	-24.74	-18.23	-29.43	-33.07
0.13 < z < 0.17			-9.62	-24.04
0.19 < z < 0.21		-24.17	-1.33	-66.23
0.23 < z < 0.27		-14.86		

4. CONCLUSIONS

In this work shelterwood or windbreak with scale model trees were used to reduce wind velocity within and above a eucalyptus forest. The results show that the shelterwood edge structure affects the wind flow within and above forest region downstream. Among the four windward edge structures tested, two showed an efficient wind velocity reduction. This trend was observed with increasing tree density. Thus, use of windbreak structure may be an alternative canopy management strategy for forest engineers to use for reduction of wind damage in forests.

5. ACKNOWLEDGEMENTS

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