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The Influence of Optical Porosity of Tree Windbreaks on Windward Wind Speed, Erosive Force and Sand Deposition

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Abstract

The research was conducted windward of an irrigated *Acacia amplicips Maslin* windbreak established to protect As Salam Cement Plant from winds and moving sands. Two belts with approximate optical porosities of 50% and 20% were studied in River Nile State, Sudan. The research aimed at assessing the efficiency of the two belts in wind speed reduction and sand deposition. Research methods included: (i) estimation of optical porosity, (ii) measurements of windward wind speeds at a control and at distances of 0.5 h (h stands for windbreak height), 1 h and 2 h at two vertical levels of 0.25 h and 0.5 h, (iii) estimation of relative wind speeds at the three positions (distance and height) at windward and (iv) estimation of wind erosive forces and prediction of zones of sand deposition. Results show that while the two belts reduced windward wind speeds at the two levels for the three distances, belt II was more effective. Nearest sand deposition occurred at 2 h and 1h windward of belt II and belt I, respectively, at level 0.25 h. At level 0.5 h, sand was deposited only at 2 h windward of belt II and no sand deposition occurred windward of belt I. The study concludes that less porous windbreaks are more effective in reducing wind speed and in depositing sand in windward direction at a distance of not less than twice the belt height.

Key Words: Erosion, porosity, windbreak, wind speed

Introduction

Sandy soils are particularly prone to wind erosion (Bird et al. 1992). Beside wind speed the erosive wind energy has the main impact on the erosion process (Klik 2008). The rate of soil movement during erosion varies directly as the cube of the wind velocity (Smith and English 1982; Das 2008; Modarres 2008) as long as the range of velocities observed is well above the threshold velocity. Most drifting sands occur near the ground within 30 cm of the ground. Reduction in wind speed near the ground is the most im-portant (Maki 1982).

Vegetation plays an important role in reducing soil erosion by wind in arid and semi-arid environments (Wolfe and Nickling 1993). As wind approaches a windbreak, some moves through the barrier but most moves up and over. This results in a reduction in wind speed both windward and leeward. On the windward side, the protected zone extends 2-5 times the height of the windbreak. On the leeward side, the protected zone generally extends 10 to 20 times the height (Gilreath 2006; USDA 2011a). The ability of vegetation to act as a windbreak for sediment has a

maximum value for an intermediate value of porosity, with porosities of approximately 20-40% showing the maximum effect (Okin et al. 2006).

The efficiency of barriers in terms of reduction of wind velocity and turbulence intensity, and hence on wind-erosion processes is determined by various factors (Cornelis and Gabriels 2005). Barrier porosity is generally considered to have the highest influence on the distribution of wind velocity and turbulence intensity (Bean et al. 1974; Cornelis and Gabriels 2005). The effectiveness of a windbreak can be expressed in terms of percentage reduction of wind velocity or the erosiveness of the wind, at distances that are multiples of the barrier height (Finkel et al. 1986). For practical engineering purposes, the overall shelter effect of a fence should include both the upwind and downwind effects (Dong et al. 2006).

Optical porosity has traditionally been used to give an estimate of the porosity of shelterbelts (Cleugh 1998). It is the important structural feature of two-dimensional artificial fences and narrow shelterbelts, but not for three dimensional or wide shelterbelts (Torita and Satou 2007). An analysis of optical porosity of the windbreak allows assessing its effect in different phonological phases (Středová et al. 2012). Unfortunately, the porosity for trees is very complex to deal with and very difficult to determine due to the irregular size and shape of the trees and varied distribution of the pores (Zhu et al. 2003; Dong et al. 2006; Bitog et al. 2012).

Measuring efficiency of windbreaks is not so often carried out in the field in the world (Mužikova and Středa 2011). Much research was done using simulation models and experimentation wind tunnels. Determination of the shelter effect by direct measurement of sand movement around fences has rarely been done (Dong et al. 2006). In arid regions, few studies have detailed the effectiveness of vegetation in controlling wind erosion (Mohammed et al. 1996).

The extensive literature on crop and soil protection from wind or advective damages by single shelterbelts deals almost exclusively with occurrences at the protected leeward side of such belts (Mohammed et al. 1995). What is more, previous studies paid little attention to the shelter effect created upwind of the fence (Dong et al. 2006). For the capturing of sand it is the wind behaviour at the windward side that is of importance (Mohammed et al. 1996). In Sudan Mohammed (1991); Al-amin (1999); Dafa-Alla and

Al-amin (2011); conducted field measurements to assess windbreak efficiency on reduction of wind speed and sand deposition. Mohammed et al. (1996) develop a conceptual model of net sand deposition around the edge of a shelterbelt (windward and inside) and suggest a design of tree shelterbelts for protection against moving sand of a multi-row, long, wide, tall shelterbelt of low permeability, and with a canopy geometry appropriate for sand protection, without gaps, while its direction should be perpendicular to the prevailing wind. The novelty of this study is attributed to its empirical field measurement of wind speed and assessment of erosion and its focus on the windward side of a windbreak grown in arid zone to protect industrial buildings from wind damage and sand invasion.

This study aimed to: (i) assess the efficiency of existing tree windbreaks in Sudan in reducing windward wind speed at multiple distances of belt height (h) at two vertical levels of 0.25h and 0.5h at morning, mid-day and afternoon times in addition to a control, (ii) estimation of erosive forces of wind and (iii) prediction of zones of sand deposition windward of the two belts.

Materials and Methods

Materials

The study was conducted in Atbara town (Lat. 17° $42'$ $0''$ N, long. 33° $58'$ $0''$ E) in River Nile state in Sudan where an irrigated tree windbreak was established in 2006 to protect As Salam Cement Plant from winds and moving sands. The complex comprises the factory and all supporting industrial services plus the housing and communal facilities. The structure of As Salam windbreak consists of two rows of *Acacia amplicips Maslin* spaced 2x2 m, planted alternatively, with varying heights and densities.

Methods

Estimation of windbreak porosity

A number of researchers have used photographs to estimate porosity by manually counting the number of grid points which fall in pores (Kenney 1987). The two belts were photographed and pictures were taken perpendicular to them keeping the sun behind to achieve maximum clearness. Belt porosities were estimated on the basis of relative percentages of foliage and pores.

Two sections (hereafter belt I and belt II) of the windbreak without gaps at the bottom, with approximate optical porosities of 50% and 20% respectively at measurement levels and a height of 4m were used for the investigation of the effects of As Salam windbreak on wind speed, wind force erosiveness and sand deposition.

Wind speed measurements

An electrical anemometer that consists of three conical cups for counting was used to measure wind speeds (m s^{-1}). The anemometer was connected to programmable CR800 data logger powered by a solar panel. The measurements were taken during winter northerly winds (6-10 January) on windward where prevailing wind was perpendicular to the windbreak.

The efficiency of a windbreak can be evaluated in terms of the ratio between the mean wind speed of the air current as obstructed by a wind barrier and the mean wind speed of the undisturbed air at a given height and distance windward or leeward from the windbreak (Cornelis et al. 1997). Vertical profiles of wind speed were obtained at the levels 0.25 h and 0.5 h. Horizontal measurements were taken at 0.5 h, 1 h, and 2 h distances in upwind direction. Reference anemometer was used in an open area for the two levels as a control. Ten minutes average wind speeds were measured simultaneously for each combination of the two levels and the three positions, and the control at three different times (morning, mid-day and afternoon) during the day for durations of two hours each.

Comparison of blowing and relative wind speeds: To assess the efficiency of the two belts in reducing wind speed, wind speeds at the control and at each of the two belts were recorded then relative wind speed (W) (as percent of open wind speed) at each position for the two levels windward of the two belts were made. T-test procedure of SPSS was used for comparison of mean speeds.

Estimation of wind speed reduction coefficients: The role of the windbreak to reduce the impact of the coming wind was assessed using wind speed reduction coefficient R (equation 1) according to Zhang et al. (1995); Zhu et al. (2002); Cornelis and Gabriels (2005)

$$R = 1 - \frac{U_{sij}}{U_{oij}} \qquad (1)$$

Where:

R = Reduction coefficient

i = level of measurement (in h)

j = distance of measurement from the windbreak (in h)

Usij = wind speed at the windbreak (average wind speeds of two hours ms^{-1})

Uoij = wind speed at the same level in the open (average wind speeds of two hours ms^{-1}).

Prediction of erosiveness of winds

Because the wind data at each point were not measured at the same time, the relative wind speed was used in this analysis (Zhu et al. 2002). Relative wind speed at the two levels for the three positions was estimated using equation 2 according to Zhang et al. (1995)

$$W = \frac{U_{sij}}{U_{oij}} \qquad (2)$$

Erosiveness of winds for loose sandy soil of the study area was considered as proportional to relative wind speed cubed (E∞W^3) according to Smith and English (1982); Bird et al. (1992); Das (2008)

Delineation of zones of sand deposition

The zones of deposited sand were predicted depending on van den Steen (1995) who observed, on a wind tunnel, that sands started to deposit at wind speed ≤ 3 ms^{-1}. Therefore, zones of sand deposition because of the presence of the windbreaks were delineated using equation 3 taking u$_{oij}$ to be 3 ms^{-1} and when $1 \geq f \geq 0$

$$f = 1 - \frac{U_{sij}}{3} \qquad (3)$$

Results

Comparisons of open and relative wind speeds

Wind speed was measured and recorded thirteen times for each combination of position and level windward of the two belts together with the control. T-test analyses of mean relative wind speeds at each of the two belts and wind speed at the controls, for the two levels and the three positions, revealed that there are significant differences ($\alpha \leq 0.05$) in mean wind speed at the control and each combination of the three positions and the two levels. Fig. 1 and 2 compare
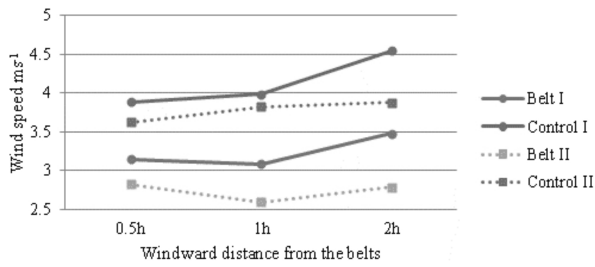
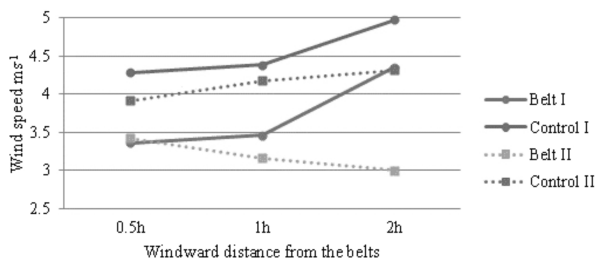**Fig. 1.** Mean wind speed at 0.25 h (h=belt height) level at the belts and controls.

Fig. 2. Mean wind speed at 0.25 h (h=belt height) level at the belts and controls.

Table 1. Reduction coefficients, erosive force and protection efficiency index of the two belts at the two levels and three positions

Belt	Level	Position	R	W	EF	f
Belt 1	0.25 h	0.5 h	0.19	81	0.53	0.0
		1 h	0.23	77	0.46	0.0
		2 h	0.24	76	0.45	−0.2
	0.5 h	0.5 h	0.21	79	0.48	−0.1
		1 h	0.21	79	0.49	−0.2
		2 h	0.12	88	0.67	−0.5
Belt II	0.25 h	0.5 h	0.22	78	0.47	0.1
		1 h	0.32	68	0.31	0.1
		2 h	0.28	72	0.37	0.1
	0.5 h	0.5 h	0.13	87	0.67	−0.1
		1 h	0.24	76	0.44	−0.1
		2 h	0.30	70	0.34	0.0

R, Reduction coefficient; W, relative wind speed; EF, erosive force; f, protection efficiency index.

mean wind speeds at 0.25 h and 0.5 h levels, respectively, for the three positions at the three positions windward and the control.

Wind speed reduction coefficients of the belts:

Reduction coefficient (R) calculated using equation 1 is shown in Table 1. Higher and better reduction coefficients were generally made by belt II for the three distances at level 0.25 h and at 1 h and 2 h at level 0.5 h.

Prediction of erosiveness of winds at the belts

Erosive force (EF) estimated at the two levels are displayed on Table 1.

Delineation of zones of sand deposition

The ability of each belt to deposit the sand load of coming wind was estimated and shown in table 1. Sand deposition occurs when specific protection index is $0 \leq f \leq 1$.

Discussion

Open, relative wind speeds and wind speed reduction coefficient

As relative wind speed and relative wind speed reduction are complementary the following discussion applies to both. While wind speeds are reduced in the windward vicinity of both belts, for the two levels and the three positions, relative wind speeds measured at level 0.5 h and 0.25 h, windward of belt I remained higher than the threshold velocity (of 3 ms^{-1} used in this analysis) of sand deposition (Fig. 1 and 2). Result indicates that belt II is relatively more effective than belt I in reducing wind speed for distances extend between 0.5 h and 2 h windward. The result agrees with (USDA 2012; Wray et al. 1997; van Eimern et al. in Mohammed et al. 1999) that the more solid or dense a windbreak, the greater the wind speed reduction and with (Vigiak et al. 2003; Takle et al. 2006) that windbreaks substantially reduce wind speed on the windward side for a horizontal distance of 2-5 h. In general the percentage reductions of wind speed made by belt I were smaller compared to belt II. Their range extend from 19-24 and 22-28, at level 0.25 h and 12-21 and 13-30 at level 0.5 h for belt I and II, respectively. Comparable results are made by (Mohammed et al. 1996) that an average wind reduction of around 20% at 50 cm height occurred between 1.5-3 h.

Higher open wind speeds at belt I at the three distances for the two levels (Fig. 1 and 2) resulted in smaller protected zone. The result agrees with Fryrear and Skidmore (1985); Van den Steen (1995), Bitog et al. (2012) that the higher the windward wind velocity, the smaller the protected horizontal distance until the velocity had almost recovered.

Prediction of erosiveness of winds

Both belts reduced wind speed at the two levels for the three positions. They produce better relative wind speeds at the three distances compared to 86%, 91% & 98% of Alhudi I belt and 93%, 90% and 91% for Alhudi II belt while wind erosiveness was reduced for a range of 45%-67% at belt I and 31%-67% at belt II (Fig. 3 and 4) compared to 64%-94% for Alhudi I and 73%-80% for Alhudi II belts (Dafa-Alla and Al-Amin 2011).

Comparable results show that wind speed is reduced to 62% of open wind speed, but the estimated erosive force of the wind is reduced to 24% of open values (Bird et al. 1992). The result demonstrates that even a small reduction ratio of wind speed could effectively reduce the erosive force of the wind and therefore help control wind erosion particularly if windward protection is considered. This result follows earlier findings by Rouse and Hodges (2004); Takle et al. (2006); Birog et al. (2012).

Delineation of zones of sand deposition

Result showed that while wind speeds are reduced in the windward vicinity of both belts for the two levels and the three positions, sand deposition occurred between distances of 0.5 h and 2 h at level 0.25 h at belt II and not before a distance of 2 h at level 0.5 h. At belt I, sand was deposited between distances of 0.5 h and 1h at level 0.25 h and no
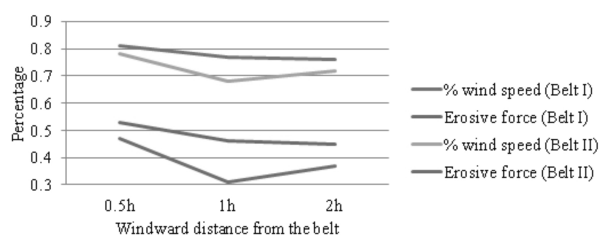
sand deposition occurred at level 0.5 h where wind speed remained higher than the threshold velocity of 3 ms^{-1}. This result support earlier finding that sand accumulation often occurs upwind of dense fences, and especially upwind of solid fences, but usually occurs downwind (behind) the fence when the porosity is sufficiently high (Dong et al. 2006; Das 2008) and that wind erosion occurs when erosive forces are higher than the soil resisting forces.

The conclusions drawn from table 1 is that belt II deposits sand windward of the belt up to a distance of 2 h at 0.25 h level and thereby provides more protection from sand to the building compared to belt I. The result concurs earlier findings that in general windbreaks with higher densities are used to protect wildlife, farmsteads or home sites (Brandle et al. 2007; Straight and Brandle 2007) and that the key design element is 60-80% density (40-20% porosity) barrier (year-round) with primary buildings/area within 2-5 times the anticipated mature height of the windbreak (Brandle et al. 2009; USDA 2011b; Wight and Straight 2013).

However, wind erosion occurred at 2 h windward of belt I at level 0.25 h and at the three positions when wind was measured at 0.5 h level. At belt II wind erosion took place at 0.5 h and 1 h closer to the belt at level 0.5 h. This supports the observation of Mohammed et al. (1996) of the occurrence of negative sand deposition (erosion) at a certain distance from the belt. They attribute that to the magnitude of the approaching wind speed and its power to induce saltating sand. Such a 'negative deposition' may occur until zones are reached that always have wind speed below the threshold Mohammed et al. (1996).
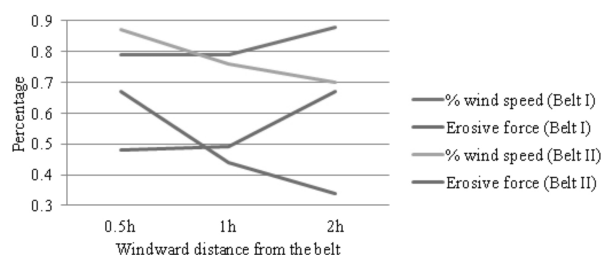

Fig. 3. Effect of belts on wind speed and erosive winds at level 0.25 h (h=belt height).

Fig. 4. Effect of belts on wind speed and erosive winds at level 0.5 h (h=belt height).

Conclusions

We concluded that both belts reduced windward wind speed at the two levels for the three positions. Belt II, which is relatively less porous, is more effective in reducing windward wind speed and wind erosive forces, and in depositing sand than Belt I. Sand deposition zones, for level 0.25 h and 0.5 h, were extended for as far as a distance of 2 h for belt II indicating the relative appropriate windbreak design for suppressing moving sand. In designing windbreaks for structural protection, therefore, a windbreaks porosity of 20-40% and location of primary buildings at a distance of not less than twice the anticipated mature height of the windbreak need to be maintained.

Acknowledgements

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