Design, Efficiency and Influence of a Multiple-Row, Mix-Species Shelterbelt on Wind Speed and Erosion Control in Arid Climate of North Sudan

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Abstract: The study aimed at assessing the design and efficiency of Alhudi shelterbelts in Semi arid zone of Northern Sudan in protecting soil erosion, suppressing moving sand and suggesting a suitable and appropriate shelterbelt design to be applicable in similar conditions at national and regional levels. Alhudi is an irrigated shelterbelt composed of six rows of tree species: *Acacia seyal*, *Acacia ehrenbergiana*, *Ziziphus spina-christi*, *Azadirechta indica*, *Conicarpus lancifolius* and *Acacia amplicips*. Based on shelterbelt configuration two well defined segments on the shelterbelt were recognized (termed belt 1 and belt 11). Wind speeds were measured on windward of both belts during north prevailing wind using CR800 programmable data logger connected to cup anemometer. Vertical measurements were taken at 0.25 and 0.5 h, horizontal measurements were taken at 0.25, 0.5, 1, and 2 h from the shelterbelt upwind and a control anemometer was placed in an open area for the two levels and distances. Ten-minute average wind speeds were recorded. The measurements were aimed to evaluate the influence of the shelters on capability of wind to erode the soil windward and create dust and sand storm or to reduce the coming wind's load capability to deposit its load (sand deposit). The capability of each belt were estimated and predicted by applying a protection efficiency model. Results indicate that species of *Acacia ehrenbergiana* and *Acacia seyal* or other species of this family are not suitable for first row of the windward of a shelterbelt. The appropriate shelterbelt design to protect buildings and cultivated fields from sand storm in arid climate of Sudan is recommended to be irrigated, of at least three rows with its height increased from outside to inside, to decrease turbulence. Shelterbelt proper management is crucial for better growth and efficiency.

Key words: Design, dry land, impact, protection, sand deposition, shelterbelt

INTRODUCTION

Windbreaks for mitigation of adverse wind effects: Shelter plantings in the world have been well researched, but little of the documented research on windbreaks relates to tropical areas (Nicholas, 1988). Most of the research has been done in Asia, Europe, and North America on the yield effects of shelterbelts and windbreaks, but only scattered data are available for African countries (Anderson, 1987). The effect, which has been much carefully quantified, is the impact of shelterbelts on soil moisture and fertility, and ultimately on crop yields (Winpenny, 1991). A literature search indicates that only very scanty data on the effects of shelterbelts and windbreaks on sand deposition is present worldwide and most of the studies were in wind tunnel experiments (Cornelis *et al.*, 1997). Field investigations indicated the effectiveness of trees and shrubs to suppress moving sand compared to other mechanical measures (Al-Amin *et al.*, 2006; Al-Amin *et al.*, 2010; Shulin *et al.*, 2008; Mohammed *et al.*, 1999). The effectiveness of a barrier depends on its porosity, however, low porosity creates turbulence on leeward (Ki-Pyo and Young-Moon, 2009). To overcome the problem multiple rows shelterbelt can be used given that its height be increased from outside to inside (Bijay *et al.*, 2009).

The shelterbelt efficiency could be assessed depending on shelterbelt impact on wind speed that can reduce wind force which erode the soil or/and carry soil particles (soil erosion, drifting sand and deposit sand and soil particles load) and some models are developed for that. Windbreak protection efficiency model (Zhang *et al.*, 1995) uses the concept of specific object to be protected (specific protection efficiency), and the specific belts protection efficiency (f) is defined as:

$$f = 1 - \frac{U_s}{U_c} \qquad (1) \qquad \text{when Us} \leq \text{Uc}$$

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$$f = 2\left(1 - \frac{U_s}{U_c}\right) \qquad (2) \qquad \text{When Us} > \text{Uc}$$

where,

Us is the shelterbelt wind speed

Uc is critical wind speeds (is available from literature, depends on the objects to be protected).

When Us>Uc (Eq. 2) a factor of 2 is applied on assumption that when Us exceeds Uc by small amount the damage exceeds the possible benefit received. When Us is slightly less than Uc by similar wind speed amount. The maximum index value i.e. protection efficiency (f) equals one for the highest protection and the negative index indicates sheltered wind speed is greater than critical wind speed (no protection is provided).

Bird *et al*. (1992) developed wind erosive force model. In this model, wind erosive force for loose sandy soil is considered proportional to cubic wind speed where small reduction in wind speed would result in large soil erosion control as follows:

$$R = \frac{W_t}{W_0} \qquad\qquad (3)$$

where,

R is wind reduction ratio

W_t is the wind speed at any level for any distance from the tree (average wind speeds of 2 h)

W_o is the wind speed at the same level in the open (average wind speeds of 2 h)

The need for proper windbreak design: Land degradation in general and moving sand, in particular, is a major problem in Sudan. A considerable area of land is swallowed annually for moving sand. Burial of irrigation canals and residential areas is wide spread across the country's arid and semi-arid zones. Despite the large magnitude of the problem, there is a lack of scientifically designed shelterbelt in general and for sand settlement in particular. In the Sudan, Mohammed *et al.* (1996) and Al-Amin *et al.* (2003) conducted researches on influences of shelterbelts on sand trapping, deposition and movement in central Sudan. Mohammed *et al.* (1999) stated, "Physical and biological techniques of protecting agricultural land from sand encroachment require through understanding of wind regimes at micro- and meso-scale levels and their amelioration". They further indicated that sand deposition around belts of different width, composition and structure has to be better understood for efficient design of protective measures. Mohammed (1991) stresses the need for cost/benefit studies of the use of the tree shelterbelt products, with farmer participation. The study aimed to assess the existing shelterbelts efficiency using Zhang *et al.* (1995) and Bird *et al*., (1992) models. Where the

shelterbelt role in protecting soil erosion suppressing moving sand will be assessed. Their growth performance will be monitored, to identify their establishment constraints in North Sudan and to suggest a suitable and appropriate shelterbelt design to be applicable in similar conditions at national and regional levels.

MATERIALS AND METHODS

Study area: This study was conducted in River Nile State (Lat.16° - 19° N, Long. 32° - 34° E) in North Sudan which accommodates petroleum pump station 5 (PS 5) at Alhudi, of about 60 kilometers northeast Atbra town. The study area lies on the fringe of the desert agro-ecological zone. The dominant topographic features around PS 5 are treeless extensive flat clay to clay loam soil. The climatic and topographic characteristics of the area have provided hostile and susceptible environment to desertification.

Alhudi shelterbelt: Alhudi shelterbelt is established, in 2003, primarily to protect the station from sand fine grains transported by wind erosion that affect the mechanical parts of the pumping units, the living conditions and pose health hazard to working staff in the residential camps. The shelterbelt was established using seedlings irrigated by drip irrigation. The total cost of establishment was about US$ 70,000.00 with an estimated annual maintenance cost of about US$ 5,580.00 (Salih, 2003). Fig. 1 and 2 and Table 1 display the components of Alhudi windbreak structure and layout. The belt, which was six years old, is composed of three indigenous and three exotic tree species, equally spaced at 3 m×3 m. Indigenous tree species used are *Acacia seyal* (Del), *Acacia ehrenbergiana* (Forsk.) Hayne, and *Ziziphus spina-christi* (L) Deaf, while exotic species used are *Azadirechta indica* A. Juss*, Conicarpus lancifolius*, and *Acacia amplicips* Maslin. The total length of the shelterbelt is around 4 km; its width varies relative to wind direction. The width varies between 24 m (6 rows) at perpendicular direction to dominant winds and 12 m (4 rows) at less disturbing winds. Along the perpendicular side, the belt density varies, depending on the species planted at first row and its growth pattern. Based on shelterbelt configuration (sequence of trees in the windbreak) two well defined segments on the shelterbelt were recognized (hereafter termed belt 1 and belt 11). Species composition of Belt 1 begins with *Acacia seyal*, while that of belt 11 begins with *Acacia ehrenbergiana* (Table 1).

Wind speed measurements: The wind speed measurements were aimed to evaluate the impact of the presence of the shelter on capability of wind to erode the soil (windward) and hence create dust and sand storm or

Fig. 1: Alhudi shelterbelt front view

Fig. 2: Alhudi II shelterbelt side view

to reduce the coming wind's load capability to deposit its load (sand deposit). Therefore, wind speeds measurements were made only on windward where prevailing wind is perpendicular to the shelterbelt. Wind speeds measurements were taken, during north prevailing wind (6-10 January 2010). Wind speeds were measured using a CR800 measurement and control system (Campell, Scientific). A data logger powered by a battery of 12V was connected to a solar panel. It includes CPU, analogue, digital inputs, and outputs. The CR800 is a programmable data logger, uses PC200 software that provides program generation and editing, data retrieval,

Table 1: Alhudi shelterbelts component, structure and general description

Shelterbelt	Species/ Rows		Height (m)	General description
Alhudi I	1	*Acacia seyal	3.0	Shelter length is about 300 m; has better
	2	Ziziphus spina-christi	1.5	growth and rather dense compared to
	3	Acacia ehrenbergianl	1.5	Alhudi belt II. Porosity at 1.5 m high
	4	Acacia amplicps	3.0	was about 55%.
	5	Azadirechta indica	3.5	
	6	Conocarpus lancifolius	2.5	
Alhudi II	1	Acacia ehrenbergiana	2.0	Length is about 500 m; porosity at 1.0 m
	2	Ziziphus spina-christi	1.5	high was about 70%; not growing well, most
	3	Acacia seyal	2.0	of the trees were defoliated and some were
	4	Acacia amplicps	3.0	dead; the first row was rather dense well
	5	Azadirechta indica	2.0	growing compared to the other rows
	6	Conocarpus lancifolius	2.0	

1-6* are the rows number from outside to inside

Table 2: Specific protection indexes (f) for drifting sand, taking the critical wind speed 4 ms^{-1} at Alhudi belt I and II, Nile Estate - North Sudan. Wind speed measured at level 0.25 h at 10 min interval and averaged for two hours for each location. $1 \geq f > 0$, higher f-value indicates better protection efficiency

Location	Alhudi belt I		Alhudi belt II	
	f-value	f-value of +ve%	f-value	% of +ve f-value
0.5 h	0.2462	100	0.067	100
1 h	- 0.0416	30	0.087	92
2 h	- 0.3205	8	0.107	92

Table 3: Specific protection indexes (f) for soil erosion, taking the critical wind speed 5.4 ms^{-1} at Alhudi belt I and II, Nile Estate - North Sudan. Wind speed measured at level 0.25 h at 10 min intervals and averaged for two hours for each location, $1 \geq f > 0$, higher f-value indicates better protection efficiency

Position	Alhudi belt I		Alhudi belt II	
	f-value	f-value of +ve%	f-value	% +ve f-value
0.5 h	0.4417	100	0.2244	100
1 h	0.2284	100	0.2393	100
2 h	0.0218	46	0.2558	100

and real timing monitoring. An electrical cup anemometer that consists of three conical cups for counting was connected to the data logger by cable reels. The measurements were made vertically and horizontally. Vertical measurements were made at two different levels with respect to the height of the belt (h), that at 0.25 and 0.5 h. Ten minutes average wind speeds were measured simultaneously for the two levels at each position, and at different times during the day for each position for duration of two hours. Horizontal measurements were taken at the following distances from the shelterbelt upwind direction in multiples of the belt height: 0.25, 0.5, 1 and 2 h. Reference anemometer was used in an open area for the two levels and distances. Since the wind speed at different positions were measured at different times within the day, assuming that the coming winds has almost the same maximum wind speed (statistically no significant differences), therefore the coming wind (wind speed at open) during the whole period of the measurements were statistically analyzed using statistical package (SPSS). The comparison between different shelterbelts was considered when the assumption was valid. For comparison, the capability of each shelterbelt to protect soil from soil erosion and drifting sand, deposit sand and to reduce erosive force of the wind were estimated and predicted by applying the windbreak

protection efficiency model developed by Zhang *et al.* (1995) and Bird *et al.* (1992), then the efficiency of each shelterbelt design was assessed.

RESULTS AND DISCUSSION

Taking critical wind speed 4.5 ms^{-1} (for drifting sand) the calculated f-values are shown in Table 2 and 3 for belt I and belt II, respectively. Belt I, showed relatively low protection near the belt, but higher f-values compared to belt II (0.246 and 0.062) for belt I and II, respectively, at distance of 0.5 h. The higher density and height of belt I compared to belt II could explain this picture, belt I has better growth and rather dense compared to belt II (height was 3 and 2 m, porosity was 55 and 70%) for belt I and II, respectively. At distances of 1 and 2 h the shelter influences for belt I were almost diminished, where 70% of f-values were negative implying that the presence of the belt has no influence. The difference in the mean wind speed of prevailing wind could explain the negative f-value. The winds speed of prevailing wind (control) could explain these results since the measurements at each belt was not taken simultaneously. During wind measurements the prevailing wind speed were lower than the critical and therefore getting small f-positive values. The wind speed reduction

Table 4: Comparisons of mean wind speeds for wind speed at open at level of 0.25 h at positions 0.5, 1 and 2 h for Belt I, Wind speed measured for 10 min intervals and averaged for 2 h at each location (h stands for belt height) (one way ANOVA)

Position	Sum of squares	df	Mean square	F	Sig.
a					
Between position	22.190	2	11.095	34.435	0.000
Within position	11.599	36	0.322		
Total	33.789	38			

Position	No. of sample	Means ms^{-1}	S.D.
b			
0.5 h	13	3.5133	0.50158
1 h	13	4.5649	0.47318
2 h	13	5.3548	0.70080
Total	39	4.4777	0.94297

Table 5a: Comparisons of mean wind speeds for open at level of 0.25 h at positions 0.5, 1 and 2 h for Belt II, Wind speed measured for 10 min intervals and averaged for two hours at each location (h stands for belt height), (one way ANOVA)

Position	Sum of squares	df	Mean square	F	Sig.
a					
Between groups	0.176	2	0.088	0.469	0.629
Within groups	6.561	35	0.187		
Total	6.737	37			

Position	No. of sample	Means ms^{-1}	S.D.
b			
0.5 h	13	4.55115	0.46624
1 h	13	4.54323	0.187000
2 h	12	4.40100	0.575183
Total	38	4.50103	0.426702

Table 6: Shelterbelts wind reduction ratio (R) and related reduction in wind erosive force (E) in semi-arid area condition of Nile Estate - North Sudan. Wind speed measured at level 0.25 h for 10 min intervals and averaged for two hours at each location (h stands for belt height)

	0.5 h		1 h		2 h	
Distance	R	E	R	E	R	E
Alhudi I	86	64	91	76	98	95
Alhudi II	93	81	90	74	91	76

Table 7: Shelterbelts wind reduction ratio (R) and related reduction in wind erosive force (E) at Alhudi belt I. Wind speed measured at level 0.25 h for 10 min intervals and averaged for two hours at each location (h stands for belt height)

	0.5 h		1 h		2 h	
Distance	R	E	R	E	R	E
Alhudi I	86	64	88	68	87	65
Alhudi II	85	62	90	73	91	76

Table 8: Shelterbelts wind reduction ratio (R) and related reduction in wind erosive force (E) at gap between trees of the first row of Alhudi belt I and belt II. Wind speed measured for 10 min intervals and averaged for two hours at each location (h stands for belt height)

	0.25 h		0.50 h	
Level	R	E	R	E
Gap I Acacia ehrenbergiana	0.96	0.88	0.91	0.75
Gap 2 Acacia ehrenbergiana	0.78	0.47	0.75	0.42
Gap 1 Acacia seyal	1.16	1.54	0.68	0.32
Gap 2 Acacia seyal	0.84	0.60	0.73	0.38

at each belt is a function of the wind speed at open (control). The models used for evaluation depends on the wind speed at the belt and does not account the actual wind speed of the blowing wind. Comparisons of mean wind speeds of the control (Table 4a, b, and 5a, b) at a level of 0.25 h at positions 0.5, 1 and 2 h, for belt I showed significant differences (p = 0.05) in mean wind speed. Multiple comparisons further indicated that mean wind speeds were significantly different at each pair of positions (Table 4 and 5).

Belt II showed positive f-values at all distance but with small f-values (0.1). Rather steady wind speed during measurements could be the reason of positive f-values at these distances. With F-value of 0.629 comparisons of mean wind speeds (Table 5a) of the control at a level of 0.25h at positions 0.5, 1 and 2 h for belt II, showed no significant differences (p = 0.05) in mean wind speed (Table 5b). Even though, both shelterbelt designs showed very small f-values implying low or no protection.

Using the same wind speed data with critical wind speed to be 5.4 ms^{-1}, dust storm was predicted and the efficiency of each belt was speculated. Belt II had f-value of about 0.2. Belt I at distance of 0.5 h had higher f- value than belt II and its f values becoming lower than belt II at distances of 1 and 2 h (Table 3). The capability of wind to create sand storm is determined by wind speed and distance the wind travel over (avalanching). Considering the height of each belt, belt II had better role in decreasing the avalanching, the reduced wind started at 6 and 3 m from belt II and belt I, respectively, which could result in small sand load of coming wind near belt II compared to belt I.

The bad growth, tree morphology and distance between seedlings explain these f-values. The species of the first row of belt II was defoliated, not growing well and some trees were dead. The dense and well growing second row of belt II could explain the positive f-values shown. Average height for the six rows was 3.5 and 3 m for belt I and belt II, respectively. It seems the height does not play a role in these belts design. The bad growth of trees is mainly due to irrigation system and water constraint. Drip irrigation in arid climate of high temperature and low relative humidity of this area and irregularity of irrigation limited the growth of the species used although the species are drought tolerant. Having six rows each of 150 seedlings per row gives a total number of 900 seedlings, therefore more water is needed that was not available most of the time since the water has to be brought from the city at 2 km from the belt.

Erosive force estimated at two levels from the soil surface of each shelterbelt is displayed in Table 6 and 7. Gaps between trees of the first row of Alhudi belts (Table 8) showed that near the soil surface (0.5h) *A. ehrenbergiana* had lower impact on wind erosive force compared to *Acacia seyal* (Talih) species. *A. ehrenbergiana* reduced the wind speed up to 78% reducing the erosive force to 47% while gaps between *Acacia seyal* (Talih) increased the wind speed to 116% thereby increasing the wind erosive force up to 154%.

Alhudi belts had bad growth performance. They consist of six rows, irrigated by drip, and during the first three years had suffered shortage of water. This showed that the main constraint for shelterbelt at this area is availability of water. The result demonstrates that even small reduction ratio could largely reduce the erosive force of the wind and therefore control wind erosion particularly if leeward protection is considered.

The adopted configuration of Alhudi shelterbelt is inefficient in reducing wind speed and sand deposition. A windbreak must be dense near the ground. For this purpose, always choose a dense, bushy deciduous or evergreen shrub for the windward row of a multiple-row planting. Results also show that although Alhudi belts I and II are made up of six rows, their growth was poor and were not effective. The amount of protection is not directly related to the number of rows but to the density or porosity of the windbreak. The effect of any barrier in reducing the rate of soil movement depends on the wind velocity and direction, the threshold velocities needed to initiate soil movement, and the barrier shape, width, height and porosity (Tibke, 1988). A five-row planting makes a very desirable farmstead windbreak. The best performance usually is obtained by using a different kind of tree or shrub in each row. Following the traditional windbreak design suitable plant combination of a multiple row irrigated shelterbelt includes a dense shrub, medium-sized deciduous, tall deciduous, medium evergreen and tall evergreen for successive rows starting windward (WSU, 2003).

In dry areas, supplemental irrigation can reduce the number of rows used in a windbreak or make the standard number of rows more effective. For example, two or three rows of trees given supplemental irrigation easily equal five rows depending only on natural precipitation. Results will be better with three rows that have room to develop than with five seriously overcrowded rows. Crowding trees in a windbreak causes a loss of vigor due to severe competition as the trees try to increase in size. Lower limbs die out early from too much shade in an overcrowded planting, thus making the windbreak much less effective because of lower density next to the ground. The seasons govern porosity of many species, and therefore influence the effectiveness of the windbreaks (Tibke, 1988). This may be true for Alhudi shelterbelt as wind speed measurements were taken during January where deciduous trees are partially shaded. However, this further calls for a better species selection and windbreak configuration.

CONCLUSION

The establishment of Alhudi shelterbelt in the hostile dry lands of northern Sudan is an achievement in itself. However, the results indicate that species of *Acacia ehrenbergiana* and *Acacia seyal* or other species of this family not suitable for first row of the windward of a shelterbelt yet they are tolerant to the climate of the area, since their growth architecture leaves gaps in between when planted at 2 m apart. Therefore, the appropriate shelterbelt design to deposit and/or to decrease wind load of sand to protect buildings, and cultivated fields from sand storm in arid climate of Sudan could be of at least three rows with its height increased from outside to inside, to decrease turbulence that can be created from one very dense row. For arid condition irrigated shelterbelts with flood irrigation system is recommended to overcome water stress. First row has to be of bushy

species that grow very dense near the surface, not defoliate and the other two rows can be made of a tree species of high stem and dense canopy. Distance within rows to be 1m and between row of 2-3 m and seedlings arranged in staggered manner. The Proper management is crucial for better growth to avoid gaps and to maintain the appropriate porosity needed.

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