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Wind reduction downwind from a savanna woodland edge

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Abstract

Traditionally known wind protection of a sparse tree canopy has been quantified by experiments in a savanna woodland edge. On the basis of the data a simple model is formulated for average wind reduction within such canopies. At a grid of points wind speeds were determined at two heights along lines perpendicular to the wind. Average wind speeds for these lines reduce approximately linearly into the woodland, parallel to the wind flow, until they become almost constant (saturation reduction). Airflow around single trees was studied for more understanding of these results. Preservation or regeneration of trees, in arrays suitable for the intended farming system, should be encouraged for wind protection in planning and developing crop land.

Keywords: airflow, isolated single trees, wind reduction, savanna woodland edge, sparse tree canopy, indigenous vegetation, parkland, agroforestry

Introduction

Natural tree cover, from forests to sparse woodlands interspersed with grassland, is of utmost important in modifying and improving the microclimate environment. In the tropics, this cover is crucial in counteracting the worst effects of erosive, torrential rainstorms, erosive winds and resulting infertile soils. The roots anchor the earth while their canopies protect the soil from the sweep of winds and splash of direct raindrops. From the point of view of survival, indigenous species, which are more adapted to the local environment than exotic ones, are often a better choice. They created conditions for their own survival and regenerated themselves naturally as long as they were not abused.

Destruction of natural vegetation, when establishing farms and residential sites or for the use of wood, is nowadays a common practice in Tanzania. Contrary to traditional practices (Stigter, 1985), development and management of farming in many parts of Tanzania take place these days without considering the retention of tree or shrub cover. This contributes to deforestation of the country. The uncontrolled destruction of natural cover is due either to loss or ignoring of knowledge of prevailing traditional agriculture or to required satisfaction of immediate needs by overexploiting the land. Lack of concern for conservation of natural resources for the present and future generations forms another reason. In addition, planning and development of larger systems is often done by foreign experts and government officers without involving local people. This has led to unnecessary destruction of indigenous tree cover. In some cases the necessity of protection is acknowledged, but rather late, and other species of trees are grown to replace the traditional ones for protection of residential areas and roads.

Although much is known of single windbreaks, as for example a review of design recommendations by Stigter et al. (1989) shows, little is known of traditional wind protection by scattered trees, which is so important in the tropics (Stigter, 1985). Jensen (1983; 1985) reviewed the very limited number of isolated studies on climatic influences of dispersed trees and concluded that no study was available on their effects on wind velocity. Stigter et al. (1993) have recently confirmed and explained this absence.

The aim of the present shelter study was to quantify the wind protection aspects of combinations of scattered trees in a few natural arrays in a savanna woodland, of densities also found in traditional Tanzanian agricultural practice. This wind protection by scattered trees was quantified for densities that diminished from what would be sufficient to what would be insufficient for protecting intercrops as well as for protection from soil erosion of bare soil.

The wind protection aspects of single trees, that have only little effects on their own, were also investigated, to show some basic functions that are important in building up of accumulated protection by arrays of trees. The most important observations on single trees are (Gross, 1987): (1) characteristics of air flow are dominated by the geometry of the obstacle; (2) the value as well as the location of the minimum wind speed depend strongly on stem height and (3) there is a reduction of wind speed within the tree crown. See Kainkwa (1992) for further details.

The mean relative horizontal wind speed (Heisler & Dewalle, 1988) or wind reduction ratio, R(x), may be defined as:

$$R(x) = U(x)/U(r) \tag{1}$$

where U(x) is the wind speed at distance x leeward of the edge of the windbreak and U(r) the approach or reference wind speed in the open, at the same height. This relative mean wind speed notation is generally used to quantify wind flow around linear windbreaks averaged over lines at distances x parallel to the windbreak. It can also be used to investigate wind speed reduction within a sparse tree canopy relative to that in the open. The wind speed, U(x), averaged over lines perpendicular to the wind at distances, x, from the windward edge into the canopy, is now related to a reference in front of the edge and not influenced by trees. Contrary to the general assumption for shelterbelts, R(x) then becomes a function of height. We will use it in that way.

A simple model can be hypothesized (Kainkwa, 1992). The average wind reduction ratio R(x) of the arrays, along a line parallel to the wind flow, may be taken to be linearly diminishing with distance x from the edge, within the region before the wind speed becomes almost constant (saturation reduction) so that:

$$R(x,h) = -K(h)x + R_0(h) \tag{2}$$

where K(h) is a proportional reduction factor and R_0 (h) is the reduction at the edge (or x = 0) of the system. K(h) can be considered as the measure of average flow response, at the heights concerned, to the presence of various types of roughness elements in the tree stands. K(h) is an alternative approach to a vertical attenuation coefficient or canopy flow index mentioned in studies on behaviour of average air flow vertically in vegetative canopies (e.g. Cionco, 1972, 1978; Pinker & Moses, 1982; Thomson & Pinker, 1975).

Materials and methods

After a long search throughout Northern Tanzania, an experimental area was detected with high wind speeds that (i) initially had areas with the required tree density that bordered areas denuded from all trees for large scale commercial wheat growing; (ii) experienced serious wind erosion problems in periods of bare soils between wheat growing seasons. Unfortunately, uprooting of trees went on even in the area provided for studying the wind protection from the trees. However, this gave us the opportunity to quantify the consequences for wind protection of diminishing tree density. As the first year was largely used to study sampling approaches and its preliminary results were very much like those obtained in the second year, we report here on the second and third year of measurements only.

The study area was within the farms of Setchet Wheat Company Limited (04°22'S, 35°14'E, 1740 m altitude). The climate is semi-arid, the rainy season from November - April. The area experiences prevailing easterly winds above mean annual wind speed (5.9 m s^{-1}) from August to November inclusive (Kainkwa, 1992). It is unfortunate that when these peak winds blow (which are normally associated with wind gusts, Stigter et al., 1993), no scattered trees of sufficient density or other protective vegetation are anymore around on the soil where the wheat is grown in the rainy season. Consequently, the almost bare soil is severely eroded by these violent and destructive winds. These soils are clay loam with good drainage.

Experiments were done in the same woodland area in three seasons when scattered tree canopies were dense (estimated 150 ha^{-1}), somewhat less dense (observed about 120 ha^{-1}, Figure 1a) and medium dense (observed about 60 ha^{-1} between edge and gap, Figure 1b), respectively in the years 1987 (September), 1988 (August) and 1989 (October), with clearly the largest difference between the last two years (Stigter et al., 1993). Such tree densities are in the range found in farmer's fields in Africa (Rocheleau et al., 1988). In the final year (Figure 1b), the area between 90 m and 140 m from the windward edge had been converted to crop land, in which all the trees were uprooted. Beyond 140 m, the woodland continued again. Irregular tree re-

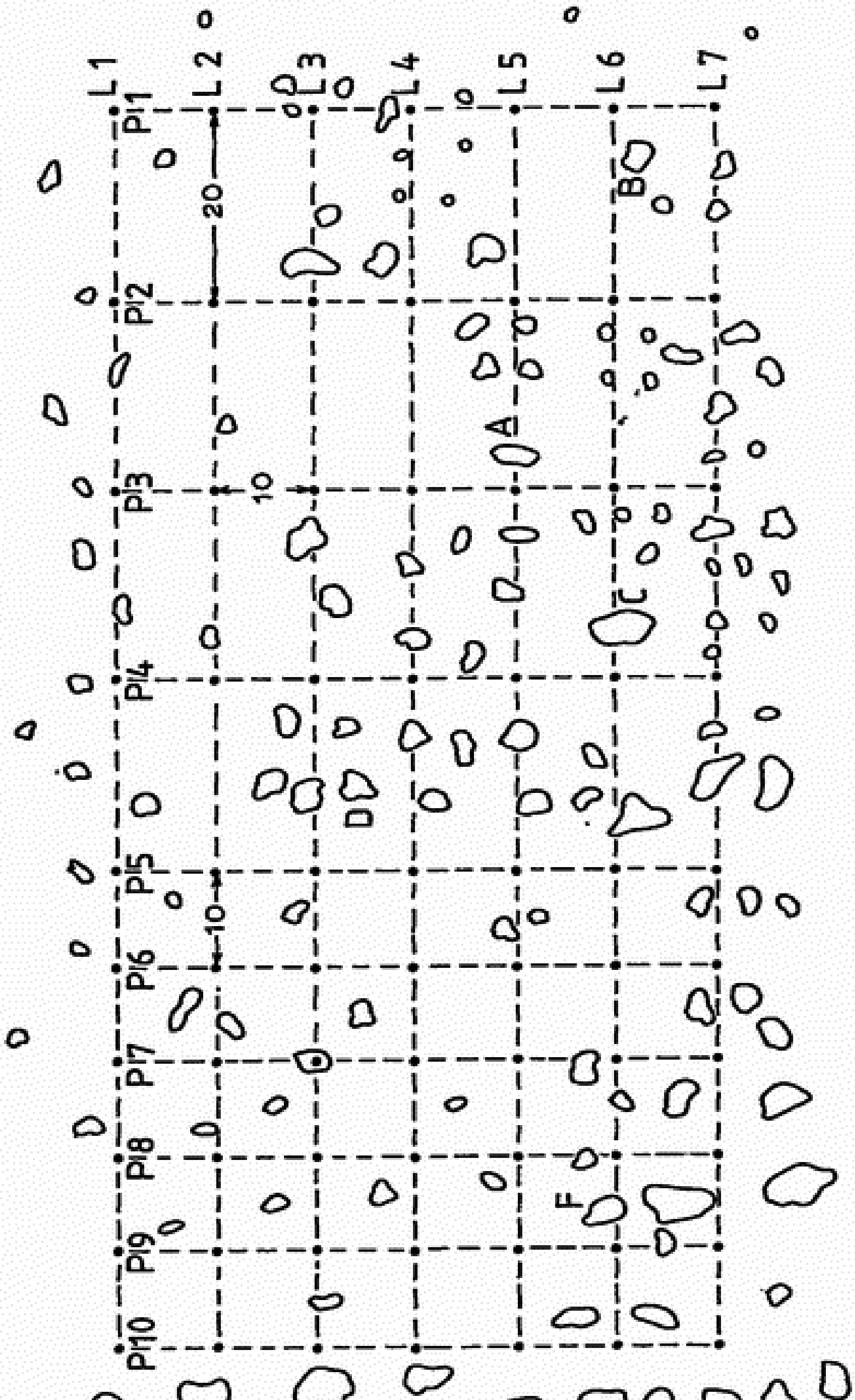

Figure 1a. A sketch of the experimental plot in the woodland showing trees (o) and layout of the anemometers (•) (situation in August 1988). Capital letters A to F are trees that may also be recognized in Figure 1b.

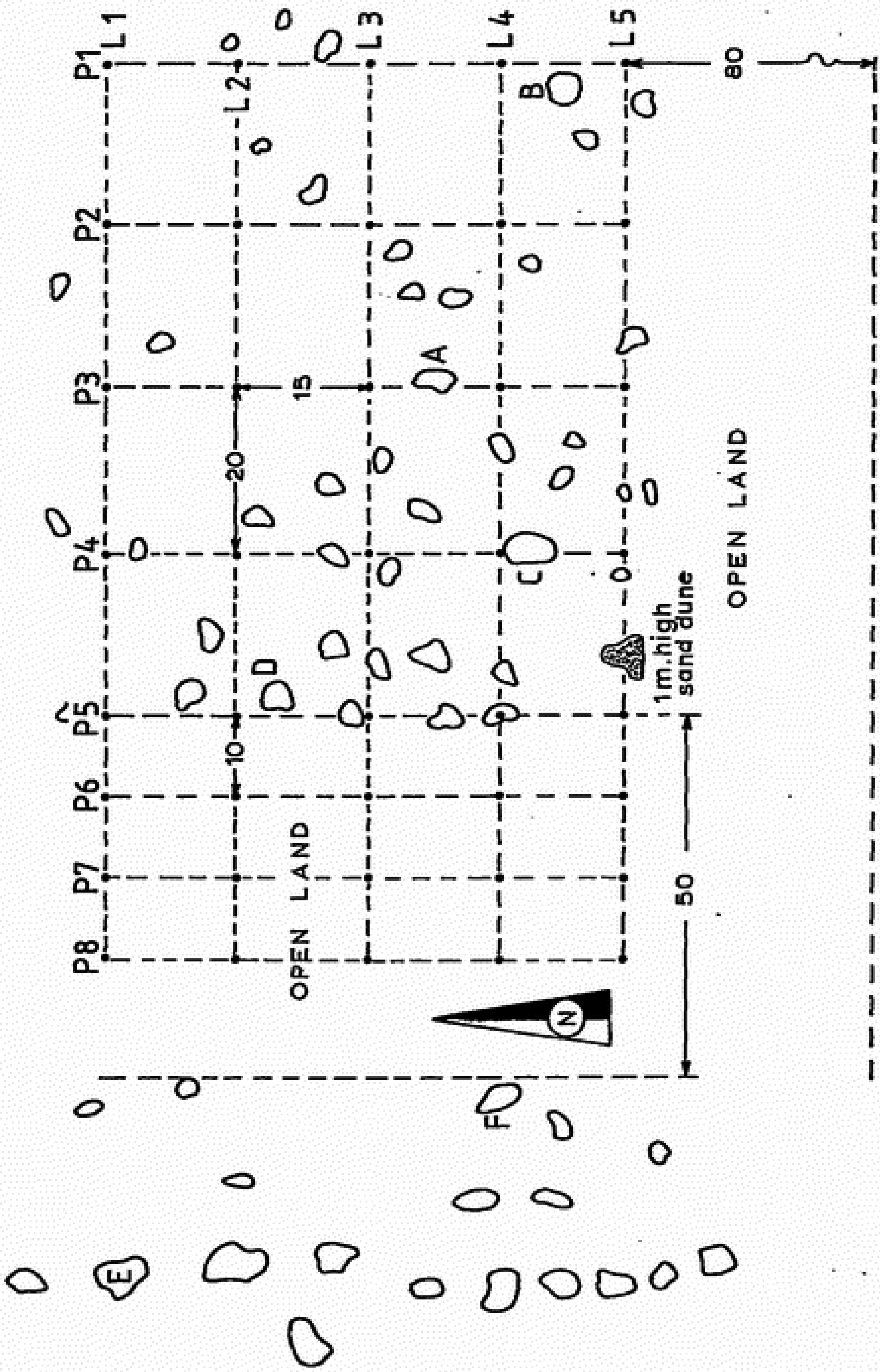

Figure 1b. A sketch of the experimental plot in the woodland showing trees (o) and layout of the anemometers (•) (situation in August 1989). Capital letters A to F are trees that may also be recognized in Figure 1a.

duction was observed in the remaining woodland (see Figure 1b).

The woodland in which the experiments were conducted (Figures 1a; 1b) was mainly composed of *Acacia tortilis* (Forsk.) Hayne and a few other savanna species such as *Acacia mbuluensis* Brenan, *Commiphora schimpere* (O. Berg) Engl. and *Balanites glabra* Mildbr. and Schlecht. The trees were randomly scattered. The mean height of the trees was 5.5 m, in which the shortest and the highest trees were respectively about 3 and 8 m. Crown diameters of the trees ranged from 2 to 9 m.

The experimental plot of the woodland edge sampled (Figures 1a; 1b) was 150 m westward by 80 m southward. Both the eastern and the northern edges faced the almost unvegetated wheat farms, for a distance of nearly 10 km. The eastern edge faced the easterly prevailing winds. Tree density as well as height somewhat increased near the edges from both east to west and north to south (Figure 1a).

Bottemanne electrical cup anemometers were used as the main indicators in the wind protection studies. They were compared and calibrated in a nearly homogeneous natural wind field at a Dar es Salaam beach with an accuracy of ± 2% (Kainkwa, 1992). In the final year, shaded Piche evaporimeters (Ibrahim et al., 1989) were also used, as auxiliary anemometers.

Wind speeds at a grid of points in the woodland were determined at heights of 1.0 m and 2.5 m along lines perpendicular to the prevailing wind (Figures 1a and 1b). From these results, wind speed reduction ratios, R(x,h), along an average line parallel to the prevailing wind were determined from the corresponding averages of these perpendicular lines. Shaded Piche evaporimeters were used in conjunction with the electrical anemometers for comparisons to evaluate their use as interpolation and extrapolation auxiliary anemometers.

A total of five different isolated single trees was involved in our earliest investigations elsewhere in Northern Tanzania. The trees had very different biomass distributions: shape, porosity, crown height, crown diameter, stem height and stem diameter (for the last four parameters see Table 1). The first and the third tree were of the same species (*Acacia mbuluensis* Brenan) but the first one was bigger than the third in all aspects. Species of the second and the fourth tree were the same (*Balanites glabra* Mildbr. and Schlecht) (compare Figures 2a and 2b) and the fifth was of a dif-

Table 1. Geometry of the single trees studied (units are in m). k = crown height, D = crown diameter, Sh = bare stem height (the point where the first branch starts), Sd = stem diameter and h = k + Sh = tree height. Above bare stem, canopy porosity increased from T_2 to T_3 (upper height), T_4, T_1 and T_5 in that order.

Tree no.	Parameter						
	k	D	Sh	Sd	h	Sh/k	Sd/D
T_1	14.2	27.0	4.8	1.1	19.0	0.34	0.04
T_2	5.1	7.6	0.6	0.3	5.7	0.12	0.04
T_3	5.0	9.0	1.0	0.3	6.0	0.20	0.03
T_4	3.1	7.5	0.9	0.4	4.0	0.29	0.05
T_5	4.2	6.0	0.8	0.8	5.0	0.19	0.13

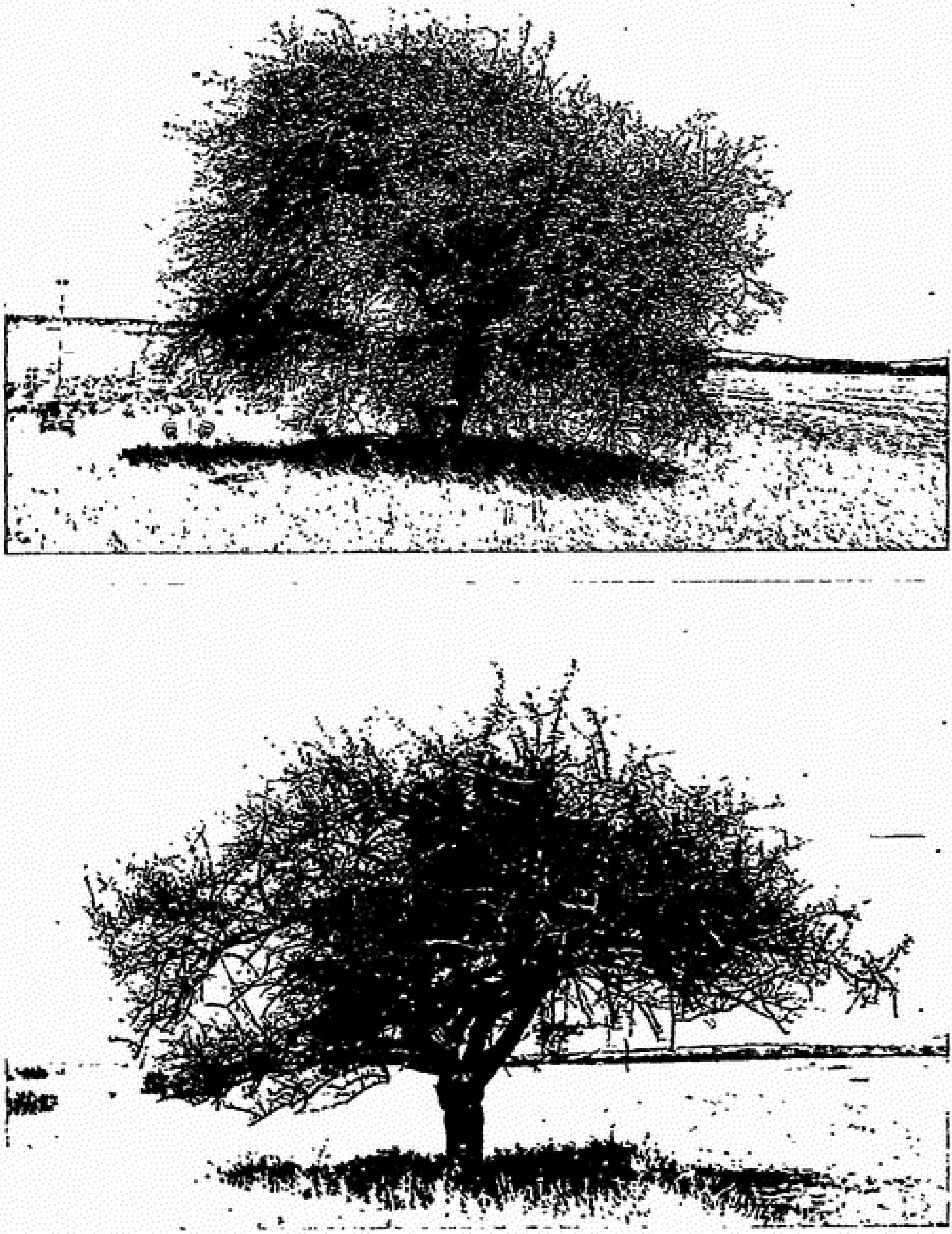

Figure 2. The two *Balanites glabra* Mildbr. and Schlecht trees.
a. T_2 - Lower porosity b. T_4 - Higher pososity

ferent species (*Erythrina caffra* Thumb).

Wind speed reduction ratios near each tree were determined at heights of 2.5 m and 1.0 m, corresponding roughly to the height of mature maize and wheat respectively. The reference anemometers were hoisted in front of the trees with respect to the prevailing wind, at least –10H from the trees, where H stands for the tree height (negative values indicate distances upwind from the tree). Wind flow around the trees was determined by installing the anemometers, 2 m apart, along lines perpendicular to the prevailing wind field. Several lines, ranging from –H to 7H, were sampled.

Results and discussion

Single trees

As may be expected, wind reduction from the isolated single trees studied was generally found to be relatively poor. Exceptions were the two Balanites glabra (Figures 2a and 2b), where the lowest reduction ratios were found (Table 2). Especially at 2.5 m height the protection was relatively good. Appreciable reduction occurred around the Balanites glabra tree with the lowest porosity, while tunnelling (see below) and other flow narrowing effects were measured at the edges of all the trees. The results (Table 2) showed appreciably greater protection at 2.5 m height than at 1.0 m, due to differences in biomass densities (see Table 1, expressed as ratios in the last two columns).

The flow field could be divided into an upper and a lower layer in which the upper flow is influenced by the higher biomass areas of the trees while that at the lower level was largely due to interaction with bare stems and tunnelling (Table 2). The narrowing of the flow in this tunnelling is due to the deviations of streamlines around the obstacles formed by the stems and the basis of crowns. This may lead to speeds even higher than the reference speed, especially at lower total friction. The results of Table 2 reinforce the observations by Gross (1987) in his numerical studies of air flow within and around a single tree as mentioned in the introduction.

Savanna woodland

For the woodland edge, wind reduction ratios, R, along average lines parallel to the prevailing wind field for two measuring sessions are presented in Figures 3 and 4.

The obviously greater R's at 1.0 m than at 2.5 m height near the edge confirm tunnelling effects underneath the upper storey of the woodland. For the year of least tree density a significant protection at saturation reduction, $R_s(h)$, was only found at the upper level of measurement. Furthermore, points of saturation reduction were observed that at 1.0 m were found deeper in the woodland than those at 2.5 m height. Eq.(2) appears valid till this saturation has been reached, after which

$$R(x,h) = -K(h)x_s + R_o(h) = R_s(h) \quad (3)$$

Table 2. Reference wind speed U(r) in m s^{-1} and wind reduction ratios, R, around trees T2 and T4. M1 till M5 are measuring points which were 2 m apart and along lines perpendicular to the prevailing wind field. M3 is closest to the stem. Averaging period was 4 hours. H = shortest distance of the perpendicular line from the tree expressed in multiples of tree height.

			T2 (September, 1987)				
			2.5 m height				
H	U(r)	M1	M2	M3	M4	M5	Av.
−0.72	8.73	0.97	0.94	–	0.88	0.93	0.93
−0.50	9.42	0.88	0.47	–	0.25	0.50	0.53
1.00	10.92	0.68	0.49	0.37	0.30	–	0.46
2.00	7.21	0.57	0.53	–	0.78	1.04	0.73
3.00	6.01	0.68	0.79	0.91	0.99	1.15	0.90
5.00	10.95	0.85	0.81	0.79	0.78	0.81	0.81
Mean	8.87	0.77	0.67	0.69	0.66	0.89	0.73
			1.0 m height				
H	U(r)	M1	M2	M3	M4	M5	Av.
−0.72	7.40	0.96	–	0.86	0.84	–	0.89
−0.50	7.85	1.10	–	0.78	0.72	–	0.87
1.00	9.02	0.94	0.77	0.73	0.57	1.00	0.80
2.00	5.97	0.72	0.70	0.70	0.80	0.91	0.77
3.00	4.91	0.67	0.77	0.87	0.97	1.02	0.86
5.00	9.07	0.91	0.83	0.81	0.80	–	0.84
Mean	7.37	0.88	0.77	0.79	0.78	0.98	0.84
			T4 (August, 1988)				
			2.5 m height				
H	U(r)	M1	M2	M3	M4	M5	Av.
−1.25	4.46	0.94	0.96	0.94	0.97	0.96	0.95
−0.85	8.02	0.95	0.90	0.89	0.94	0.95	0.93
0.50	5.54	0.99	0.43	–	0.39	0.72	0.63
1.00	4.10	0.74	0.43	0.35	0.72	0.92	0.63
2.00	3.55	0.86	0.91	0.91	0.94	0.91	0.91
3.00	4.65	0.89	0.86	0.85	0.85	0.88	0.87
4.00	3.69	0.94	0.97	0.96	0.96	0.95	0.96
Mean	4.86	0.90	0.78	0.82	0.82	0.90	0.84
			1.0 m height				
H	U(r)	M1	M2	M3	M4	M5	Av.
−1.25	3.68	0.95	0.97	0.89	0.89	0.88	0.92
−0.85	6.59	1.06	0.91	0.85	0.89	0.89	0.92
0.50	4.61	1.14	1.06	1.05	0.78	0.83	0.97
1.00	2.33	1.07	1.04	0.95	0.89	0.97	0.98
2.00	2.68	0.93	0.93	0.91	0.92	0.93	0.92
3.00	3.93	1.00	0.86	0.82	0.82	0.86	0.87
4.00	2.95	0.96	0.98	1.00	1.01	1.10	1.01
Mean	3.82	1.02	0.96	0.92	0.89	0.92	0.94

The average parallel line during the somewhat decreased tree density situation of the second year (Figure 3) showed that the minimum length of the woodland which provides a maximum of somewhat more than 50% wind reduction (saturation reductions near to 0.45) is about 110 m at 1.0 m height and about 80 m at 2.5 m height.

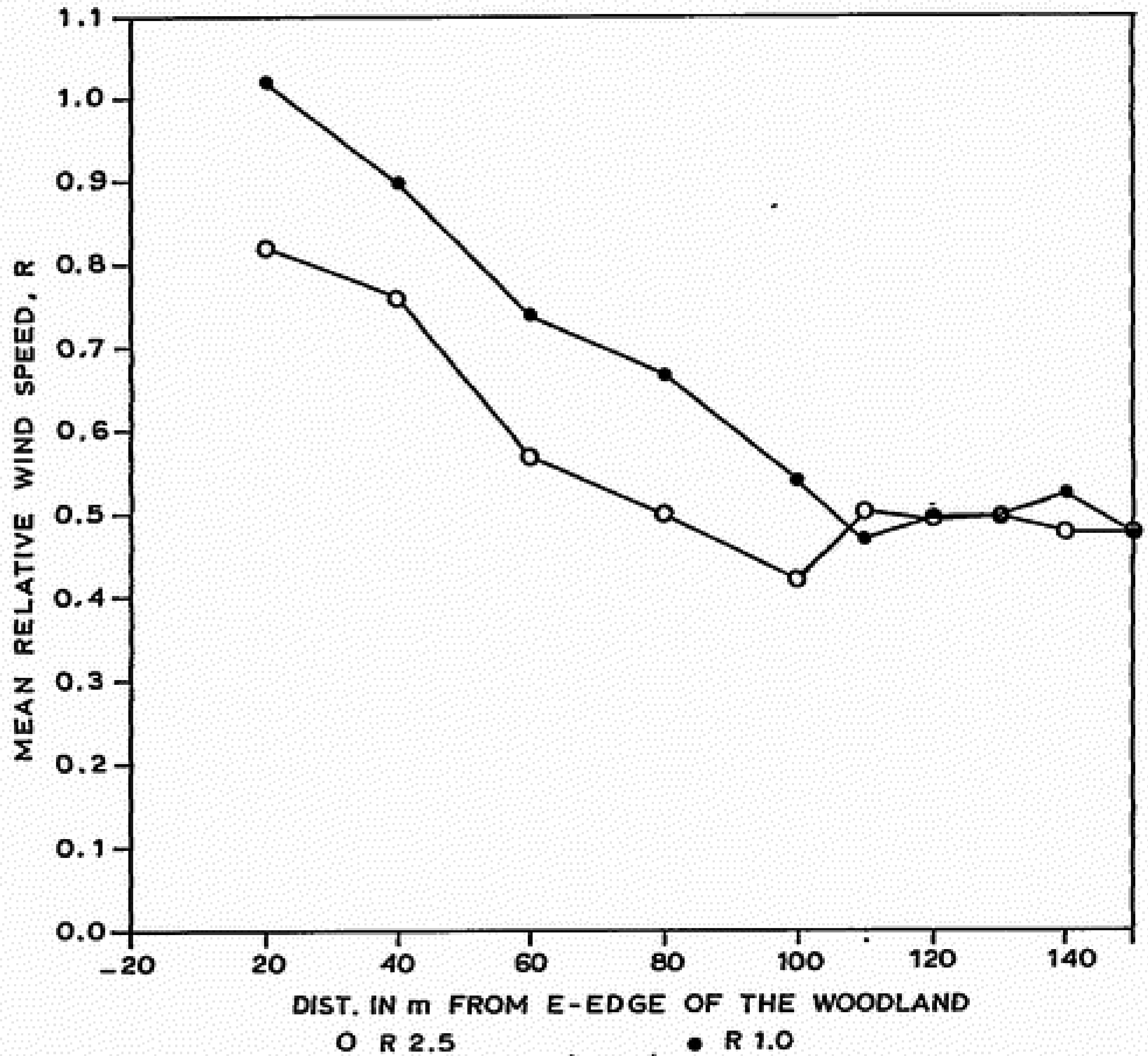

Figure 3. Wind reduction ratios, R, at heights of 2.5 m and 1.0 m as a function of distance from the windward edge into the woodland for an average parallel line (situation for 1988) as pictured in Figure 1a. During these measurements, average wind speed (in m s^{-1}) at the reference point was mostly within 8.1 ± 0.4 and 6.5 ± 0.8 at 2.5 m and 1.0 m, respectively.

$R_s(h)$ reached as high as 0.85 at x = 100 m for 1.0 m height and 0.7 at x = 70 m for 2.5 m height in the last year (Figure 4). These reductions appeared to continue over the gap of 50 m.

The relations in Eq. 2 and Eq. 3 were overall fairly satisfied by the results of the average parallel lines, during both years. For the upper height from 20 m beyond the edge, the K(2.5)-value was on the average 0.005 (a reduction of 0.05/10 m) in the last two years, despite the thinned woodland in the final year. The tunnelling at 1 m height in the first year gave a comparable reduction rate {K(1.0) = 0.006} to somewhat deeper into the canopy. In the final year, however, increased tunnelling reduced K(1.0) appreciably.

The above indeed proves quantitatively that non-homogeneous 'associated trees' such as in agroforestry situations may give a substantial wind reduction, just like

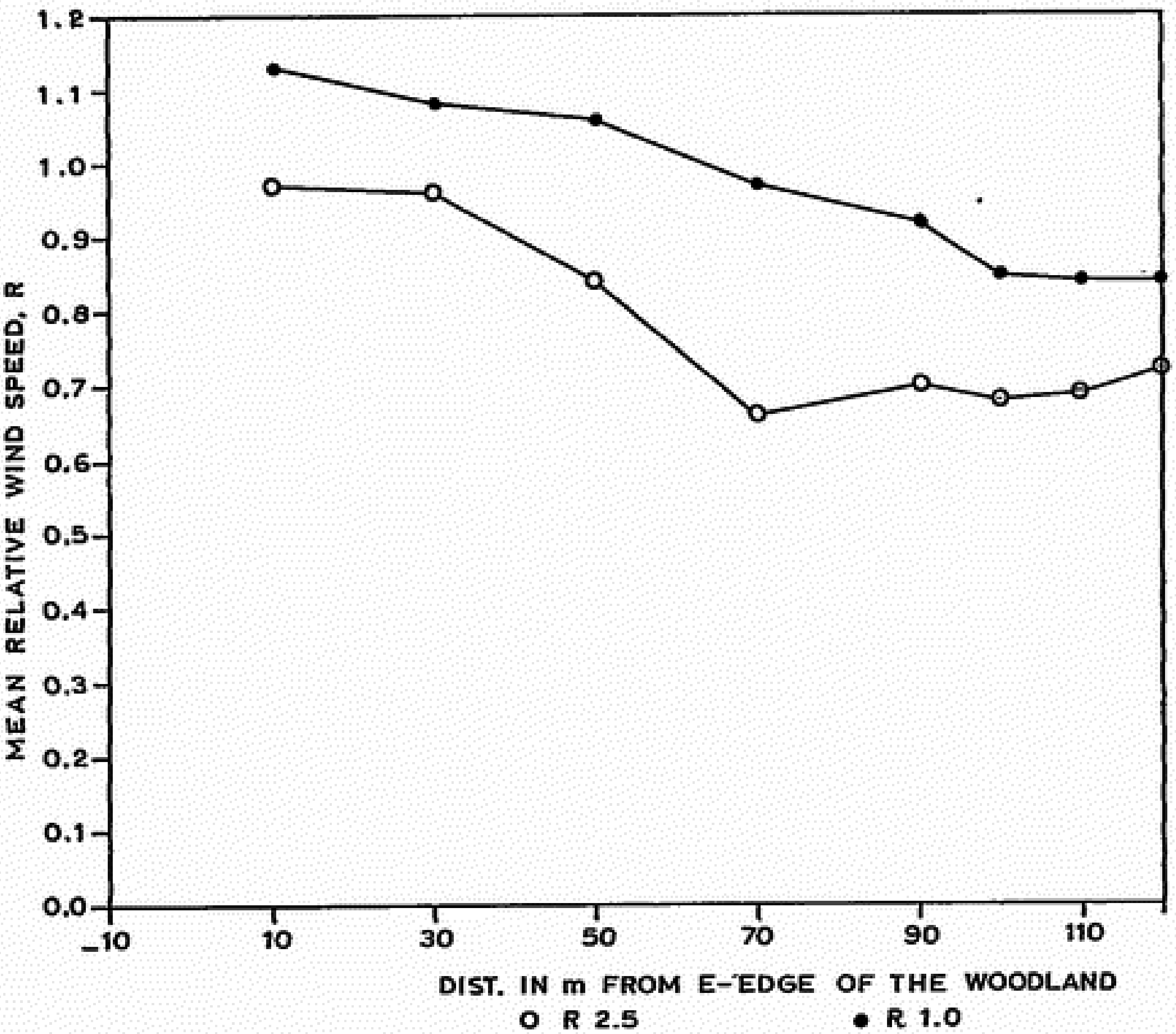

Figure 4. Wind reduction ratios, R, at heights of 2.5 m and 1.0 m as a function of distance from the windward edge into the woodland for an average parallel line (situation for 1989) as pictured in Figure 1b. During these measurements, average wind speed (in m s^{-1}) at the reference point was mostly within 7.1 ± 1.1 and 5.6 ± 0.8 at 2.5 m and 1.0 m, respectively.

shelterbelts, as suggested from experience and circumstantial evidence (Baldy, 1985; Rocheleau et al., 1988; Kerkhof, 1990; Baldy & Stigter, 1993), if they have an appropriate tree density, such as in our first two years. Traditional farmers indeed are famous for their knowledge on such gradients in their fields (Stigter, 1985).

Intercomparison with Piches

Using the square root of mean wind speed dependence of evaporation from the Piche atmometers (Ibrahim et al., 1989), wind speed and wind gradients in the woodland could be predicted fairly accurately for long enough periods of measurement and large sets of measuring points. The method of correlating reduction ratios of the two instruments (Bottemanne and Piche) appears superior to correlating actual wind speed data. The use of shaded Piche atmometers for measuring or interpolating/extrapolating wind speed (gradients) in agroforestry systems is recommended, provided that temperature and relative humidity gradients as well as differences in turbulence are not too high, as usually is the case, and an error of the order of 10% is acceptable. Details may be found again in Kainkwa (1992).

Final remarks

The data indicate how protection by a combination of trees in randomly scattered form, like in a savanna woodland, becomes significantly higher than for the single trees. This is of course due to their collective effect in wind reduction. These results add especially quantitatively to the meagre information available on horizontal wind profiles within non-homogeneous agroforestry situations and systems (e.g. Stigter, 1994).

From the wind protection aspects of such arrays of trees, we propose that small African farmers should be encouraged to keep or replant dispersed trees of appropriate densities, as they traditionally do, in their cropped fields and gardens in areas that (may) suffer from soil erosion and other wind damages to insufficiently protected fields (compare also Rocheleau et al., 1988; Kerkhof, 1990; Stigter et al., 1993). In areas where large scale mechanized farming is practised, multiple shelterbelts from indigenous trees, perpendicular to the prevailing wind at distances between 10H and 15H, or networks of perpendicular belts in cases of unreliable wind directions are recommended for wind protection (e.g. Stigter et al., 1989). It is strongly emphasized that trees should be kept or planted when planning and developing such farms. Economic efficiency of such belts or networks can eventually be improved by intercropping non-indigenous trees and having a good number of *Balanites glabra* Mildbr. and Schlecht, a local species which proved to be very good in wind protection.

The influence of tree (crown) management and of finding optimum tree combinations and planting densities in scattered form, are suggested as possible subjects for further studies on wind protection.

The need for education from experience on the potential of using or imitating natural vegetation in preserving and maintaining soil productivity for sustainable agricultural production, is emphasized. Collaboration between three kinds of environmental managers is needed: traditional farmers, dedicated extensionists and scientists that wish to contribute to solving local environmental problems in agricultural production.

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