Int. Agrophysics, 2000, 14, 457-468

MEASURING WIND GRADIENTS IN AGROFORESTRY SYSTEMS BY SHADED PICHE EVAPORIMETERS. II. ACCURACIES OBTAINED IN SOME AFRICAN CASE STUDIES

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Accepted January 3, 2000

Abstract. Accuracy levels of measurements with the Piche evaporimeter as an ancillary anemometer for the interpolation and/or extrapolation of wind speed levels, in combination with electrical cup anemometers, were determined. Data from the shaded coffee in Lyamungu (Tanzania) showed that this procedure had more than 10% accuracy for daily average levels at individual experimental sites, as long as wind speed did not drop too often below 0.75 m s^{-1}. For short runs, this accuracy was noticeably lower but improved to the same order of magnitude when using wind speed reduction ratios of the two types of anemometers. Such improvements were confirmed by the data taken in a Savanna woodland in Setchet (Tanzania) and in a complex agroforest system with hedges and intercropped trees in Matanya (Kenya). However, within a multiple shelterbelt system at Yambawa (Nigeria), under high advective conditions and high gradients of advection between the belts, the Piche system was generally not usable, and neither were ancillary anemometers with high variations during rainy season. Only homogeneity of permeability of the belts could be well determined with the Piches. Earlier results obtained in a shelterbelt in Sehaimab (Sudan) proved that application of a reference for the agroforest systems was more accurate than using a reference outside them, which was confirmed by the data from Kenya and to a certain extent also by the data obtained in Nigeria.

Keywords: agroforest systems, anemometry, cup anemometer, Piche evaporimeter, wind reduction

INTRODUCTION

After outdoor validation of the relation between the shaded Piche evaporation on the square root of wind speed [3], actual accuracy levels of using the Piche for the interpolation and/or extrapolation of wind speeds in combination with electrical cup anemometers were determined. Preliminary results of the first sets of experiments, in Lyamungu and Setchet [3], showed that correlation of reduction ratios of the squared Piche evaporation with wind reduction ratios determined with the cup anemometers [1] was much more successful. Another application of the Piche showed that the use of a reference Piche in front of an agroforest system was less accurate than using a reference from within the system [1,4,5].

Therefore, in the second phase of the TTMI-Project (1992 - 1998), two more experiments were designed, in the framework of studies covering the microclimate of two very different agroforest systems, to test these results [6,9]. Below there is a complete report on these data. Sofar only a synopsis has been published [13]. The results of using the Piche for extrapolation of wind reduction in the *Eucalyptus microtheca* shelterbelt used to cause sand deposition to protect irrigated fields from sand invasion [5].

MATERIALS AND METHODS

Theory

Accuracy levels of interpolation were first determined for a part of data used for the validation of the relation between the Piche evaporation and the square root of the wind speed obtained with cup anemometers [1]. This is permitted since the relationship was not derived from these data but was theoretically established and experimentally tested earlier for the isothermal flows with reduced turbulence [3,11].

Wind (speed) reduction ratio, $R(\mathrm{x})$, in sheltered environments is defined as wind speed at a point x, $U(\mathrm{x})$, relative to that at a reference point r, $U(\mathrm{r})$, outside or inside that sheltered environment [1,10], with means:

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

With the square root of mean wind speed, the relation of Eq. (2) in [3] is valid, and with b identical and a=0 for the simultaneously measured data, approximated as isothermal and without humidity gradients, this can be written as:

$$R(\mathrm{x}) = [E_p(\mathrm{x})]^2/[E_p(\mathrm{r})]^2 \qquad (2)$$

with $E_p(\mathrm{x})$ and $E_p(\mathrm{r})$, the Piche evaporation levels at the points x and r respectively. Or ideally

$$R_{sa} = [R(\mathrm{x})]^{0.5} = E_p(\mathrm{x})/E_p(\mathrm{r}) \qquad (3)$$

When we calculate R_{sa} as the square root of $R_a = R(\mathrm{x})$, for each measuring point of an electrical cup anemometer in a series, with respect to its chosen reference, and determine $R_p = E_p(\mathrm{x})/E_p(\mathrm{r})$, we can investigate correlation between these two wind reduction expressions from the two types of instruments.

Agroforest systems used in the experiments

Tanzania

The first agroforest system in which the cup anemometer/Piche comparison was conducted was the coffee with shade trees system at the Agricultural Research Institute, Lyamungu (03° 14' S, 37° 15' E, altitude 1250 m), on the slopes of mount Kilimanjaro. Coffee plantations at this station are similar to the traditional coffee farms in the Kilimanjaro region, characterized by the use of shade trees, grown originally to protect non-fertilized coffee trees from high solar radiation. These trees are also valued by farmers for their wind protection just before heavy rain storms. The mean annual wind speed at this location is as low as 1.4 ms^{-1} [1]. The system was shown in Fig. 1 of the companion paper [3].

The other Tanzanian system was the savanna woodland edge within in the premises of Setchet Wheat Company Limited, Hanang (04° 22' S, 35° 14' E, altitude 1740 m). Contrary to the first site, this location experiences high prevailing easter winds above the mean annual wind speed (5.9 ms^{-1}) from August to November, inclusive [1]. A gradual wind reduction downwind near the edge and reduction of the saturation wind deeper in this woodland, make it suitable for intercropping or for grazing. These wind patterns were earlier reported in [1,3,12]. A reduced tree distribution in the last year of measurements, and the lines along which the anemometers were mounted in the measuring section in that year are given in Fig. 2 of the companying paper [3].

Kenya

The data collected in Matanya, the Laikipia region, central Kenya (0° 04' S, 36° 57' E, altitude 1840 m) were obtained in a complex agroforest system with *Coleus barbatus* hedges (live fences) and intercropped *Grevillea robusta* trees, protecting maize/bean intercrop from wind damage and preventing mulch material and top soil from removal (Fig. 1). The design was not ideal for the maximum wind protection, but the gradients of wind reduction were clearly detected [10]. The system was described in detail in [9]. The layout of the anemometers used is also given in Fig. 1.

Nigeria

The data collected in Yambawa (12^{o} 27' N, 08^{o} 32' E, altitude 550 m), 75 km northeast of Kano, northern Nigeria, were obtained in an arrangement of multiple *Eucalyptus camaldulensis* shelterbelts between which millet (*Pennisetum typhoides*) was grown in the rainy season. They prevented further desertification in the dry season. It was found out that for the appropriate protection, the distance between shelterbelts should be reduced, or scattered trees should be grown between the present ones [8]. The system was shown in [8] and described in detail in [6]. The layout of the anemometers used is explained in the legenda for Fig. 2.

Experimental approach

Tanzania

The instruments used in the Tanzanian experiments has already been described [3]. In Lyamungu we used the data sets D with high correlation, and G with low correlation from Table 1 in [3]. Run C7 was used as the one with the highest average wind speed and high correlation from Table 2a in [3], together with C11 sets with high correlation and C21 with low correlation from Table 2b in [3]. The purpose was to determine accuracy of the inter- and/or extra-polating wind speeds at certain sites with the Piche evaporimeters as compared to other places where measurements had been taken earlier with cup anemometers.

For all the runs the first sub-set: D1, G1 etc., consisted of cup anemometers A1, A4, A9 and A12. In the second sub-set: D2, G2 etc., the anemometers A6 and A11 were added to those of the first sub-set. In the final sub-set: D3, G3 etc., again two anemometers: A3 and A8, were added to those of the second sub-set. These combinations were selected on the assumption that they had been exposed to appreciably different air movements (Fig. 1 of [3]). The data of each sub-set were used to determine the regression constants a and b of Eq. (2) given in the reference [3]. They were subsequently used with the Piche evaporation in other sites to determine wind speed U_{pi}, which was then compared to that of the cup anemometer at that same spot, U_{ca}. It appeared that including (0,0) produced insignificant differences in these results. Therefore, it was abandoned in the case of the Lyamungu data sets. Subsequently, for C7 also R_{sa} and R_p were correlated.

The Setchet data were worked out in the same way [1], for each of the height levels separately and including (0,0) because that improved the ratio of U_{pi} and U_{ca} in this case. Here, the anemometer in the front together with the one at L3, together with L3 and L5 (Fig. 2), were used to obtain correlations. The selected series were P4 and P7. P4, a 13.5 h run, had the lowest correlation (0.81) at 2.5 m height [3] and at 1.0 m height all the correlations were 0.93 at the best (also for P41), apart from the measuring line P1 (Fig. 2 in [3]) before the wind met the trees. P7 had an even lower correlation at 1.0 m (P71, 0.91, influenced by the Piche vibrations [3]) but a high one for P72 (0.98).

Also for some of the Setchet data, R_{sa} and R_p were correlated. This was first done for P42, P41, P72 and P71 separately. Subsequently, it was done for the average parallel line for which each point was determined as an average wind speed from five simultaneously measured points on the lines perpendicular to the prevailing wind (Fig. 2 in [3]).

Kenya

In semi-arid Matanya, in the rain shadow of Mt. Kenya, the wind protection in the cropping systems is necessary between June and September [10]. The mean maxima weekly average of wind speed were between 4 and 4.5 ms^{-1} and the mean minima between 1.5 and 2 ms^{-1}, so the square root of the wind speed relationship holds

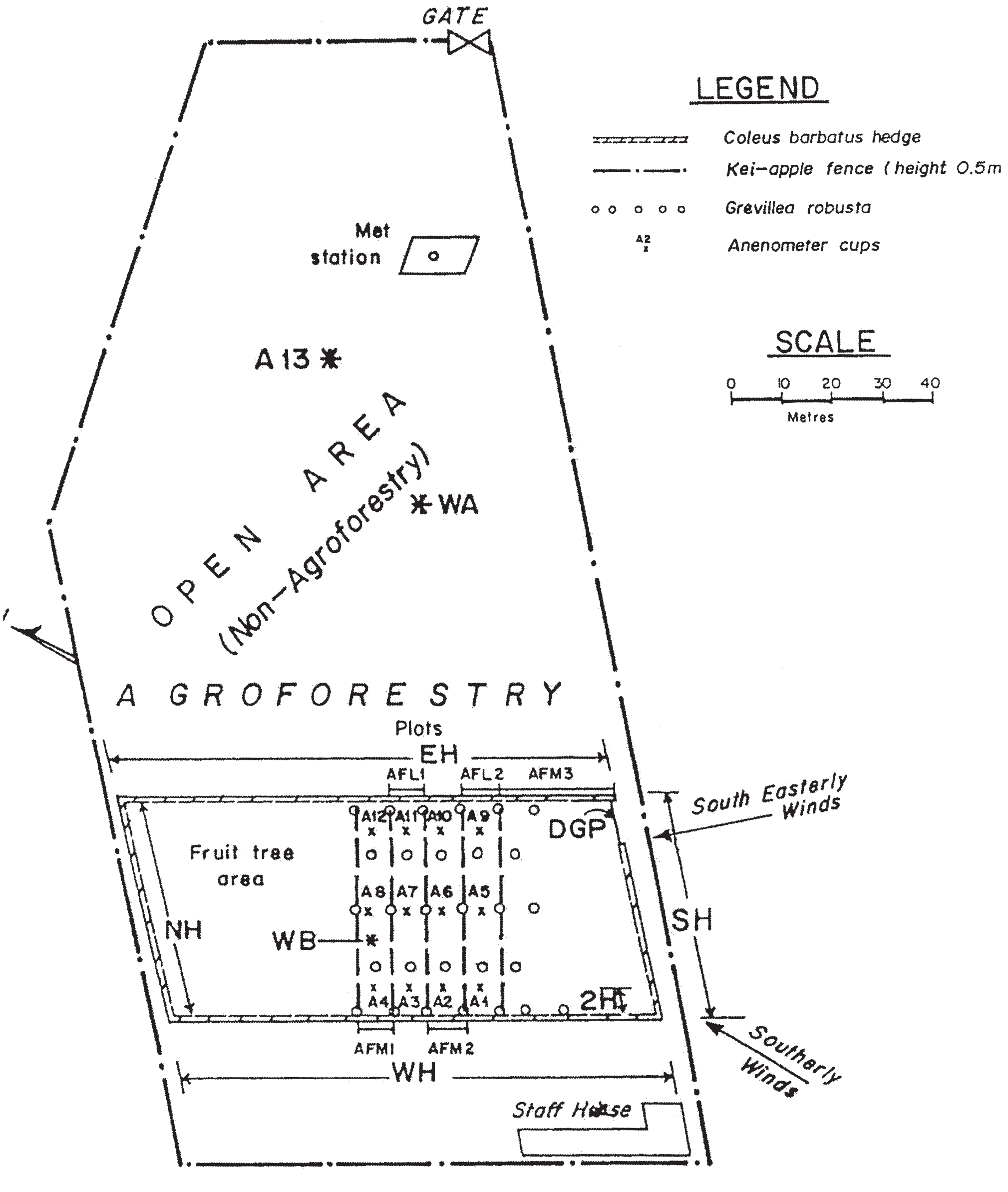

Fig. 1. Layout of instrument positions in Matanya, Kenya, in a hedged maize/bean intercrop with additional intercropped trees. Positions A1 till A13 were the ones used for the twinned cup anemometers and Piche evaporimeters. Anemometers were kept 20 cm above the highest maize growing in the agroforestry plots [9,10].

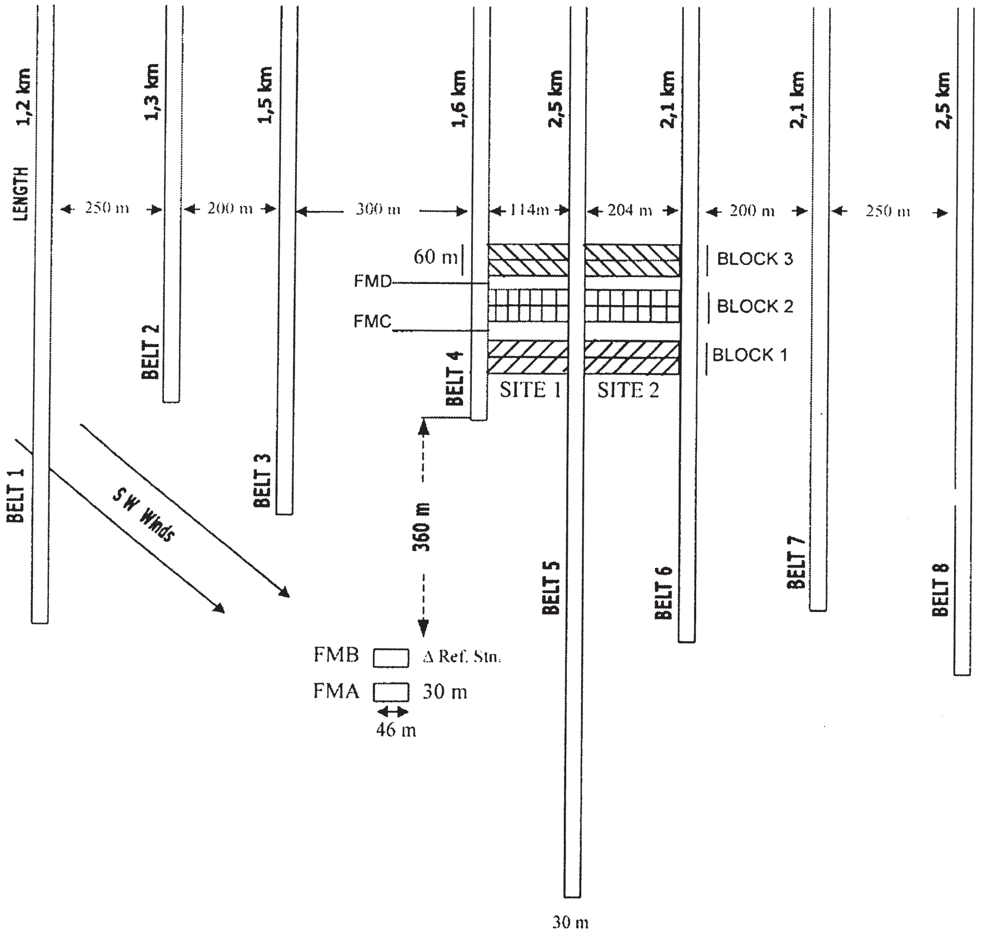

Fig. 2. Layout of instrument positions between the Yambawa shelterbelts in northern Nigeria. FMA .....FMD were farmer managed fields, outside (FMA, FMB, near a Reference Station) and within (FMC, FMD) the influence of the experimental BELTS. BLOCKS 1, 2, 3 were researcher managed fields [6, 8]. The twinned anemometers were in the middle of BLOCK 2 between BELT 4 and BELT 5 (SITE 1) in 1993 and between BELT 5 and BELT 6 (SITE 2) in 1994. In 1993 they were at the distances 1, 1.5, 2, 4, 6, 7, 8 and 8.5H (H = height of the shelterbelts) from BELT 4 and in 1994 at 1.5, 3, 5, 7.5, 9.5, 12, 14 and 15.5H from BELT 5. In both years there were also twinned anemometers at 2H (1993) and 1.5H (1994) in the middle of FMC and FMD. The anemometer sensors were kept at 2.20 m height throughout.

for the Piche throughout. The same arguments used for the Setchet data for the inclusion of (0.0), with no contribution of free convection in any of the data, is valid here as well. Instruments were discussed in [9] and [10]. Thirteen electrical mini-cup anemometers (type WV 100R, Department of Meteorology, Wageningen Agricultural University, Netherlands) were connected to a Campbell Scientific data logger (type CR10, Campbell Scientific Ltd., Shepshed, UK), powered by a solar panel (Siemens Solar GmbH, Munich, Germany) backed up by a battery system with load safety margins. A laptop computer (type Compaq 286) was used to download and process the data from the data logger. Data were taken over periods of 15 min and averaged hourly. The system was a wind tunnel calibrated in Wageningen and field calibrated on Wangu Embori farm, on the slopes of Mt. Kenya [9,10].

R_{sa} and R_p were correlated for the pooled data of twice twelve weeks in two subsequent rainy seasons. Two references were used, one outside the system in the open (A13) and one within the system (A7) (Fig. 1). The wind direction in the first year was very predominantly from the south with non-negligible but diminishing south-easterly components, strong in June but almost vanished in August. In the second year June had dominant winds from the south but also strong south-westerly components that remained in July, with equally strong components from the south and the south-east, while the latter were very dominant in August [10]. These variable wind directions guarantee strong variations in the average wind reduction from week to week and from year to year, giving the worst case for the correlation conditions. These correlations were subsequently used to calculate actual wind speed reductions from those of the Piches, which were then compared with wind speed reductions measured by cup anemometers at the same place.

Nigeria

The Yambawa multiple shelterbelts were of importance to redress serious desertification in the area. Coarse sandy soils are highly deficient in organic matter and prone to desertification and wind erosion, aggravated by the hot dry air blowing in the region for most of the year. When the grasses returned to definitely settle the sand between the belts, the area became again suitable for growing millet between the belts, which were expected to protect crops from serious dry air advection. Farmers quickly found the wind protected area to be very limited in extent, not much more than 5 times H, the height of the belts (12 m), between 60 to 70 m. They also experienced that the protected area suffered from yield reducing factors that our research found to be due to root competition from the shelterbelts [7]. This made it necessary to prune the lateral roots of the trees at the edges of the belts, at three meter distance from the belts. These belts, of different lengths, were 30 m wide and between 115 and 300 m apart (Fig. 2).

The equipment used was similar to that used in Matanya Station, Kenya. It was also a wind tunnel calibrated in Wageningen, The Netherlands, and it was field calibrated in Yambawa outside the influence of the belts. For the growing season, mean monthly wind speeds in an area unprotected by the belts were between 2.7 and 1.9 ms^{-1} from June till October 1993, respectively between 2.8 and 1.5 ms^{-1} for the same period in 1994. For the least protected areas between the belts this was between 1.9 and 1.0 (1993) and 2.3 and 1.4 ms^{-1} (1994). On a (monthly average) hourly basis, the maximum in areas unprotected by the belts reached 3.7 ms^{-1} for both years before noon. Periods with such wind speeds below 0.7 ms^{-1} only occurred at night and were rare before October, but this situation was different between the belts. However, also very high (mean monthly) hourly lapse rates, up to 0.7 $^oCm^{-1}$, particularly early and late in the growing season, and an oblique wind reduced the protected areas behind the belts.

The above figures mean that these were the most difficult conditions for the use of the Piche evaporimeter as an ancillary anemometer. High gradients in turbulence as a function of distance from the belts occur, high evaporation itself is due to high air temperatures and dryness of the air, while wind and advection gradients that exist are occurring at relatively low wind speeds. In 1993, differences of only up to 35% in evaporation occurred as a function of distance from the belt and this was mainly caused by high values at 6H, due to the start of the wake zone and larger turbulence there [7]. In 1994 such a narrow peak was absent in the measurements, due to another distribution of measuring points between belts, that were further apart. The wind speed maximum was larger and the wind speed differences were also larger.

Weekly averages of the Piche evaporation rates were linearly regressed against the square root of the wind speed at various places between the belts for the two years of measurement. The (0,0) point was not included because neither the arguments used in [3] for the Lyamungo conditions (high humidity at zero wind speed) nor those used in [3] for the Setchet conditions (no contributions of free convection) - which arguments could also be used as arguments above for the Kenyan data - are valid under the highly advective dry air conditions in Nigeria. Subsequently, the same was done for R_{sa} and R_p, with 2H and 6H in 1993 and 1.5H in 1994 and 12H were used as references. Finally, these same reduction ratios, for the data from 19 weeks in 1993 and 18 weeks in 1994, were correlated, for a few distances separately. This was done for 2H, 6H and 8H distance from the belt in 1993 and for 1.5H, 12H and 14H in 1994. The references for these reduction ratios remained the same: wind speeds at 2H and 6H for 1993 and at 1.5H and 12H for 1994. Such references were excluded in the comparisons where they occurred as reference. The homogeneity of the permeability of the belt was also determined with Piche evaporimeters, at three places at the distances of 2H in 1993 and 1.5H in 1994.

RESULTS AND DISCUSSION

Tanzania

Table 1 summarizes the results obtained for the Lyamungu data sets. It appears that only for the D run, that represents a nearly one day case with all wind speeds near or above 0.75 ms^{-1}, the inter- and extra-polated data obtained from the Piches were always within 4% on average from the cup anemometer data, individual differences being 9, 7 and 7% at the maximum when using 8, 6 and 4 sets of anemometers for the correlations, respectively. This is a very promising result because only a limited number of anemometers was needed for these full day averages. When the wind speeds get appreciably lower, like in the G run, with the maxima below 1 ms^{-1} and the minima near 0.5 ms^{-1}, where the wind dependence of evaporation is different, the accuracy drops considerably. This is true also for longer period averages, and is, on average, not better than about 15 ± 1%. Again, the number of anemometers used for the correlations is here not of influence and the limitations must be elsewhere, inherent to the validity of the method itself.

For shorter runs the results are generally much worse, also for the C7 run with wind speeds near or over 0.75 ms^{-1}. It gave average errors of between 15 ± 3% and 42 ± 4%. The number of anemometers used for the calculation has some influence but the actual limitation must be in the duration of the run.

When the points at different heights were separated, the use of 2 anemometers for the correlation to obtain data for the 4 others and the use of 3 anemometers to obtain the 3 others, were rather unsuccessful for the selected P4 and P7 lines perpendicular to the wind. An exception was P72, the upper level of P7. The maximum error in P72 for all the places was here 11% when using 3 anemometers and only 7% when using only 2 anemometers for the correlation, average absolute errors being 5% and 4% respectively. P7 was a measuring line after the first area with trees had been passed. For P42, the use of 3 anemometers in the correlation gave an average absolute error of 11% and the maximum individual error of 15%. The use of 4 anemometers gave a worse result. Apparently jetting, turbulence and Piche vibrations at the 1.0 m height and gradients in turbulence at the 2.5 m height limit the use of the correlation, but the low number of points was also involved.

Table 2 shows the correlation for run C7 between R_{sa} and R_p. The maximum error of any point in calculating wind speed reduction from Piches was 12% and the average error was 5.5%. This is a huge improvement compared to the inter- and extra-polation accuracies of wind speeds of the same run, which were of the order of 40% (Table 1, underreading).

Table 3 shows such results for the limited number of points of the P41, P42, P71 and P72 runs. The maximum individual errors still range from 6% (P41, P72) to about 20% (P42, P71) but the average errors were respectively reduced to 3±1% and 11±1% for these sets of

Table 1. Results of correlating U_{pi}, wind speed obtained from the linear regression of E_p with $U^{0.5}$, and U_{ca}, wind speed measured by electrical cup anemometers, for the selected Tanzanian data sets. With a the Y-intercept, b the slope of the line, r the correlation coefficient, EY the standard error of the Y estimate and EX the standard error of X. W is the average of $|1 - U_{pi}/U_{ca}|$ for each inter- or extra-polated anemometer, in %. The U_{pi} and the U_{ca} given here are averages for the anemometers inter- and extra-polated. P data sets come from Setchet, the others are from Lyamungu

Run	a	b	U_{pi}	U_{ca}	r	EX	EY	W
D1	0.12	0.86	0.98	1.02	0.99	0.05	0.04	4
D2	0.02	0.96	0.98	1.00	0.99	0.08	0.05	4
D3	0.08	1.04	1.05	1.09	1.00	0.05	0.03	5
G1	0.21	0.83	0.79	0.69	0.83	0.23	0.10	16
G2	0.20	0.83	0.75	0.67	0.73	0.39	0.13	16
G3	-0.31	1.40	0.70	0.72	0.91	0.45	0.13	14
C71	-0.34	0.95	0.79	1.19	0.97	0.10	0.10	36
C72	-0.42	0.96	0.72	1.19	0.98	0.10	0.09	43
C73	-0.47	0.99	0.64	1.12	0.98	0.15	0.11	47
C111	-0.30	1.38	0.83	0.82	0.96	0.17	0.16	18
C112	-0.27	1.37	1.04	0.82	0.95	0.22	0.16	12
C113	-0.37	1.55	0.79	0.75	0.97	0.30	0.18	18
C211	-0.15	1.06	0.70	0.80	0.87	0.25	0.24	33
C212	0.08	0.75	0.68	0.79	0.82	0.26	0.21	28
C213	-0.05	0.79	0.63	0.73	0.78	0.45	0.32	38
P411	0.06	0.95	4.68	5.63	0.98	0.10	0.55	23
P412	-0.02	1.09	5.69	5.25	0.99	0.12	0.55	11
P421	0.42	0.77	4.23	5.08	0.88	0.25	1.33	23
P422	-0.37	1.23	5.04	4.48	0.92	0.36	1.46	21
P711	0.86	0.62	4.61	5.70	0.93	0.14	0.93	18
P712	0.45	1.00	5.32	4.73	0.97	0.19	0.88	20
P721	0.07	0.98	5.48	5.74	1.00	0.05	0.30	4
P722	0.09	0.92	5.01	5.29	0.99	0.07	0.35	5

Table 2. The correlation for run C7 of (i) R_{sa}, the square root of wind speed ratios R_a, obtained from the wind speeds measured in the Lyamungu coffee cum shade trees agroforestry system relative to the reference wind speed, and (ii) the ratio of Piche evaporations, R_p, simultaneously obtained at the same places (meanings of regression symbols as in Table 1)

R_a	R_{sa}	R_p	R_p/R_{sa}
1.06	1.03	1.08	1.05
1.02	1.01	1.08	1.07
0.98	0.99	1.00	1.02
0.49	0.70	0.69	0.99
0.43	0.66	0.62	0.93
0.46	0.68	0.62	0.91
0.60	0.77	0.69	0.90
0.63	0.79	0.77	0.97
0.58	0.76	0.77	1.01
0.62	0.79	0.69	0.88
0.95	0.98	0.92	0.95

a=1.22 b=-0.20
EY=0.04 EX=0.10
r=0.97 W=5.5

runs, down from the order of 5 to 25%. Even more astonishing is the result from Table 4. In that particular case for the average line parallel to the wind, the individual maximum errors became 10±1% and the average error was reduced to ± 4%, with ± 5% for the height of 2.5 m and ± 3% for 1 m height.

Kenya

Table 5 shows average results of the linear correlation of weekly average R_p^2 and R_a for the pooled months June till August of two subsequent years, 1993 and 1994, that is for two times twelve weeks. The improvements obtained by the inclusion of the zero point and by using a reference from within the agroforest system (cases 2 and 4) are particularly revealing. Exclusion of the anemometers in row 2 (cases 3

Table 3. The same parameters as in Table 2, for P41, P42, P71 and P72 runs, each in five points relative to the reference in front of the edge in the Setchet savanna woodland experiment

	R_a	R_{sa}	R_p	R_p/R_{sa}		
P42	0.76	0.87	0.95	1.09	a=0.17	b=0.70
	0.55	0.74	0.68	0.92	EY=0.11	EX=0.37
	0.34	0.59	0.57	0.97	r=0.74	W=12
	0.63	0.79	0.66	0.83		
	0.99	1.00	0.79	0.79		
P41	1.15	1.07	1.12	1.04	a=0.12	b=0.88
	0.81	0.90	0.94	1.05	EY=0.05	EX=0.21
	0.64	0.80	0.80	1.00	r=0.93	W=4
	0.97	0.98	0.94	0.96		
	1.26	1.12	1.06	0.94		
P72	0.83	0.91	0.86	0.94	a=0.13	b=0.83
	0.69	0.83	0.83	1.00	EY=0.02	EX=0.09
	0.50	0.70	0.72	1.02	r=0.98	W=3
	0.52	0.72	0.71	0.98		
	0.91	0.96	0.93	0.97		
P71	1.00	1.00	0.92	0.92	a=0.56	b=0.36
	0.76	0.87	0.91	1.04	EY=0.02	EX=0.06
	0.50	0.71	0.81	1.14	r=0.97	W=11
	0.54	0.73	0.81	1.11		
	1.40	1.18	0.98	0.83		

Table 4. The same parameters as in Table 2, using the averages for the perpendicular lines, simultaneously taken at Setchet, as an average for a line parallel to the prevailing winds of which the points have not been simultaneously taken, at two heights: P21...P28 for 2.5 m and P11...P18 for 1.0 m

	R_a	R_{sa}	R_p	R_p/R_{sa}		
P21	0.97	0.98	1.00	1.02	a=-0.22	b=1.20
P22	0.96	0.99	0.99	1.01	EY=0.03	EX=0.09
P23	0.84	0.91	0.86	0.94	r=0.96	W=4
P24	0.66	0.81	0.73	0.90		W=5 for P21
P25	0.70	0.84	0.80	0.96		W=3 for P11
P26	0.68	0.83	0.75	0.91		
P27	0.69	0.83	0.81	0.97		
P28	0.72	0.85	0.81	0.95		
P11	1.13	1.07	1.04	0.97		
P12	1.08	1.04	1.03	0.99		
P13	1.06	1.03	1.01	0.98		
P14	0.97	0.98	0.97	0.99		
P15	0.92	0.96	0.92	0.96		
P16	0.85	0.92	0.82	0.89		
P17	0.84	0.92	0.89	0.97		
P18	0.84	0.91	0.91	1.00		

and 4), that hold the reference cup A7, is of particular importance because we end up here with correlations as high as 0.95 (without (0,0)) and 0.999 (with (0,0)) for the case with a reference within the agroforest system.

Table 6 shows average percentage differences for the 24 weeks as shown in Table 5, which are (i) in most cases somewhat higher measured average wind speeds in the anemometer row 2 (from anemometers A5, A6, A7 and A8), and (ii) the wind speeds obtained using Piche evaporation reduction ratios and the regression parameters of Table 5 in Eq. (2) in [3], for the same places. Again, inclusion of the zero is distinguished from the calculations without it. The results show rather low maximum errors, of -6 ± 1%, all for A8. With the prevailing wind directions, A8 had the lowest wind speeds and must be expected to have had the highest turbulence after the wind had reached this point and started to interact with more biomass than for other places. The other errors are mostly -3 ± 2% without inclusion of (0,0) and -2 ± 1% with it. There are no or very small differences when the same row 2 is excluded from the regressions (cases 3 and 4 in Tables 5 and 6). This small underreading of the Piches observed earlier must be due to differences in the time constants of the two instruments in turbulent wind. These results indicate the absence of serious systematic biases and errors in the comparisons, with the improvements due to inclusion of the (0,0) as an exception.

Table 5. Linear regression parameters of correlating R_p^2 and R_a (equivalent to correlating R_p and R_{sa} in Tables 2 to 4) for 24 weekly average wind speeds in the complex agroforestry system in Matanya, Kenya, as an average for all anemometers involved. Cases 1 and 3 are for data with the reference anemometer outside the AF system, while for cases 2 and 4 a reference from within the system was used. For cases 3 and 4 the row holding the reference anemometer was not included in the calculations. The regression parameters are identical to those describing the correlations in Table 1. Values in the second line give the results obtained after inclusion of the (0,0) point

Case	a	b	r	EX	EY
1	0.39	0.53	0.762	0.14	0.03
	0.02	0.97	0.991	0.04	0.03
2	0.11	0.86	0.920	0.12	0.01
	0.00	0.99	0.998	0.02	0.02
3	0.38	0.57	0.832	0.12	0.02
	0.01	0.98	0.993	0.03	0.03
4	0.10	0.87	0.951	0.09	0.01
	0.00	0.99	0.999	0.01	0.01

Table 6. Average percentages difference between 24 weeks of average wind speeds measured, in the complex agroforestry system in Matanya (Kenya), with cup anemometers in row 2 of Fig. 1, and those obtained from regressions with the Piche evaporation reduction ratios over the same period at the same places

Case	Without (0, 0)				With (0, 0)			
	A5	A6	A7	A8	A5	A6	A7	A8
1	-4	-4	-1	-2	-1	-2	-1	-5
2	-4	-5	-3	-7	-2	-3	-1	-6
3	-2	-2	+2	+1	-1	-2	0	-5
4	-4	-5	-3	-7	-2	-3	-1	-6

Nigeria

The average correlation of the square root of wind speed and Piche evaporation of the weekly averaged values for the nine measuring points between the belts improved from a low 0.81 in 1993 to a more reasonable 0.91 in 1994 for the reasons already given earlier. The correlations were particularly low in the months with the lowest wind speeds and high lapse rates (September and October of 1993). Outside those months the average correlation was 0.89 in 1993, with the lowest value in June, that had the highest lapse rates. For July and August 1993, the average correlation was 0.90.

However, even in these two best months, no improvement occurred for the Nigerian data when wind speed reduction ratios R_{sa} were correlated with evaporation reduction ratios R_p. It remained 0.90 with 2H as a reference and was even lower (0.88) with 6H as a reference, 6H being the distance to the shelterbelt with highest turbulence intensity, so the highest advective effects [5,8]. For all the weeks pooled, on average the correlation was 0.68 with 6H as a reference, down from 0.81 with 2H as a reference. The 6H point behaves as if it does not belong to those between the shelterbelts [6,8]. This result, therefore, confirms to a certain extent that improvements occur when using a reference from within the system. In 1994, for the same two best months of July and August, the correlation of U with E_p was 0.93 and remained at that value for the correlation of R_{sa} with R_p, independent of the reference used, while the other months were much worse.

If these latter parameters were correlated for the average wind speeds for the 19 weeks in 1993 and the 18 weeks of 1994, all the correlations dropped to 0.50 and below, as may now be expected already from the high differences detected over the months in these respective years. Apparently, the Piche evaporimeter is no longer a very suitable ancillary anemometer between the Yambawa shelterbelts, under the strongly advective conditions and their high gradients between the belts, and for the climatic variations occurring from just before to just after the short rainy seasons.

Three Piches at distances of 2H (belt 4, in 1993) and 1.5H (belt 5, in 1994), covering a distance of 70 m parallel to the belts had the maximum difference of 0.1 mm of evaporation among each other in average weekly Piche evaporation over the full seasons. In 1993 this was closely the same for the months July and August but in 1994 the difference was much smaller for these months. Such a difference is within the accuracy margins of the instruments determined by small differences in temperature and humidity alone. Given the persistent wind direction over these periods, these small differences show the permeability of the belts to be very homogeneous and constant. The differences between electric anemometer data for the same positions and periods were within less than 0.01 ms^{-1}, so far within the accuracy limits of the instruments. It may be concluded that the Piche evaporimeter was accurate enough for the assessment of homogeneity of permeability of the belts [6].

CONCLUSIONS

The conditions that follow from the above results for the accurate use of Piche evaporimeters as ancillary anemometers, using the simple square root of wind speed dependence of their evaporation, are: (i) long runs, for high humidity conditions and low wind speeds, (ii) wind speeds mainly above 0.75 ms^{-1}, (iii) no jetting due to tunneling effects, (iv) no strongly advective conditions/gradients and (v) no comparisons of weekly averages over periods that are highly different in weather conditions unless these variations are similar at the places compared. The limitations can be understood from the physics of the instrument as captured in Eq. (1) of [3]. Using correlations of wind speed and evaporation reduction rates improves the accuracy where the system itself works properly. Adding (0,0) as a measuring point where it is physically allowed highly improves accuracies.

Laminar boundary conditions in common forced convection with only relatively small contributions from free convection, as already proven and discussed in [11] for indoor conditions, have to exist. When $e_s/T_s - e_a/T_a$ (Eq. (1) in [3]) is not conservative, as under strongly varying weather, or is not changing identically, the Piche system will not be sufficiently accurate, as the Nigerian data show. Accuracies to be expected under proper conditions in agroforest systems are exemplified by the data reported in this paper. Using a reference from within the system in the correlation of ratios does increase the accuracy also. With this understanding gained, the cheap Piche evaporimeter can be used for wind speed and wind speed gradient inter- and extrapolations in agroforest systems, where wind protection is always an important factor. The number of expensive electric wind sensors, such as cup anemometers, can this way be considerably reduced.

ACKNOWLEDGMENTS

The authors thank the Setchet Wheat Company Limited, Hanang, Tanzania, leadership and staff of the Agricultural Research

Station, Lyamungu, Tanzania, of the Laikipia Research Programme, Nanyuki, Kenya, and of the Kano State Department of Forestry, Kano, Nigeria, for their collaboration during the years of our experiments. The Traditional Techniques of Microclimate Improvement (TTMI)-Project, in which context the Ph.D. -research, on parts of which we report here, took place, was core funded by the Directorate General of International Co-operation (then DGIS/DST/SO) in the Ministry of Foreign Affairs, The Netherlands.

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