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Performance of the Main Materials Used in Dune Stabilization in the Sahel, Niger

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Abstract

Dune fixation is one of the most effective ways of combating sand encroachment in the Sahel. However, the specific role of the materials used in dune stabilization and vegetation recovery remains poorly documented. In this study, the performance of the main fixation materials, *Leptadenia pyrotechnica* branches and *Hyphaene thebaica* rachis, was assessed through an experimental setup over two seasons (2014-2015) on an active dune field. Three common combinations were tested: windbreak fences made from *L. pyrotechnica* branches (P LP), windbreak fences made from *H. thebaica* rachis (P RHT), and windbreak fences of *L. pyrotechnica* branches combined with a paving of *H. thebaica* rachis (P LP/RHT). On average, 10 branches of 650 g ± 6.8 g are needed to erect one linear meter of P LP at 1.7 m in height (average porosity: 18.4% ± 1.2%), and 29 rachis of 227.7 g ± 0.57 g for one linear meter of P RHT at 1.4 m (initial porosity: 18.45% ± 4.74%). The paving requires about 6 rachis per square meter. In 2014 and 2015, these installations allowed for the collection of 1080 $kg \cdot m^{-1}$ and 940 $kg \cdot m^{-1}$ of wind-blown sediments, respectively, at −5 m from the first windbreak fence. Reductions in wind-blown sediment flux at 15 m downwind reach 96.18% for P LP/RHT, 93.91% for P LP, and 90.67% for P RHT, compared to the flux measured at 5 m upwind. After the first rainy season, the highest dry biomass yield was recorded with P LP/RHT (322.90 kg/ha ± 102.04 kg/ha), followed by P LP (213.98 kg/ha ± 82.20 kg/ha) and P RHT (132.93 kg/ha ± 59.11 kg/ha). The installation of these windbreak fences promoted improved seed retention, reduced aeolian flux, enhanced soil surface stability, and created a microclimate more conducive to seed germination and the development of herbaceous vegetation.

Keywords

Dune Fixation, Windbreak Fence, Aeolian Flux, Revegetation, Sahel Niger

1. Introduction

Dune stabilization is a technique designed to immobilize the sand of active dunes and promote their ecological rehabilitation. The main objective is to prevent aeolian sand movement long enough to allow natural or planted vegetation to be established. This practice is part of ecological restoration efforts, which emerged when humans recognized the need to repair environmental degradation caused by their activities [1]. Attempts to stabilize dunes have been documented for several centuries in multiple regions around the world [2]-[4].

A wide range of techniques and materials are used to combat wind erosion, particularly in the Sahelian region, where sand encroachment is a major concern. These methods are adapted to soil characteristics, resource availability, and conservation goals, and they function by reducing wind speed and promoting sediment deposition [5]-[7]. They are especially important when infrastructures, productive lands, or natural resources are threatened [8].

In Niger, especially in the southeastern areas, dune stabilization targets active dunes that act as sources of drifting sand. Restoring long-term vegetation cover is the most effective strategy [9] [10]-[12], but it requires preliminary mechanical stabilization of sand mobility [8]. Mechanical fixation reduces the erosive forces of wind and protects soil moisture by either erecting linear barriers perpendicular to prevailing winds or covering dune surfaces with protective materials, typically of plant origin [8] [13]-[15].

In this region, branch material from *Leptadenia pyrotechnica* and rachis elements from *Hyphaene thebaica* are the most used resources, arranged as linear fences or surface coverings. These structures stabilize sand and create a favorable microclimate that fosters seed germination and herbaceous vegetation recovery, generally observable during the first rainy season following installation [16]-[19].

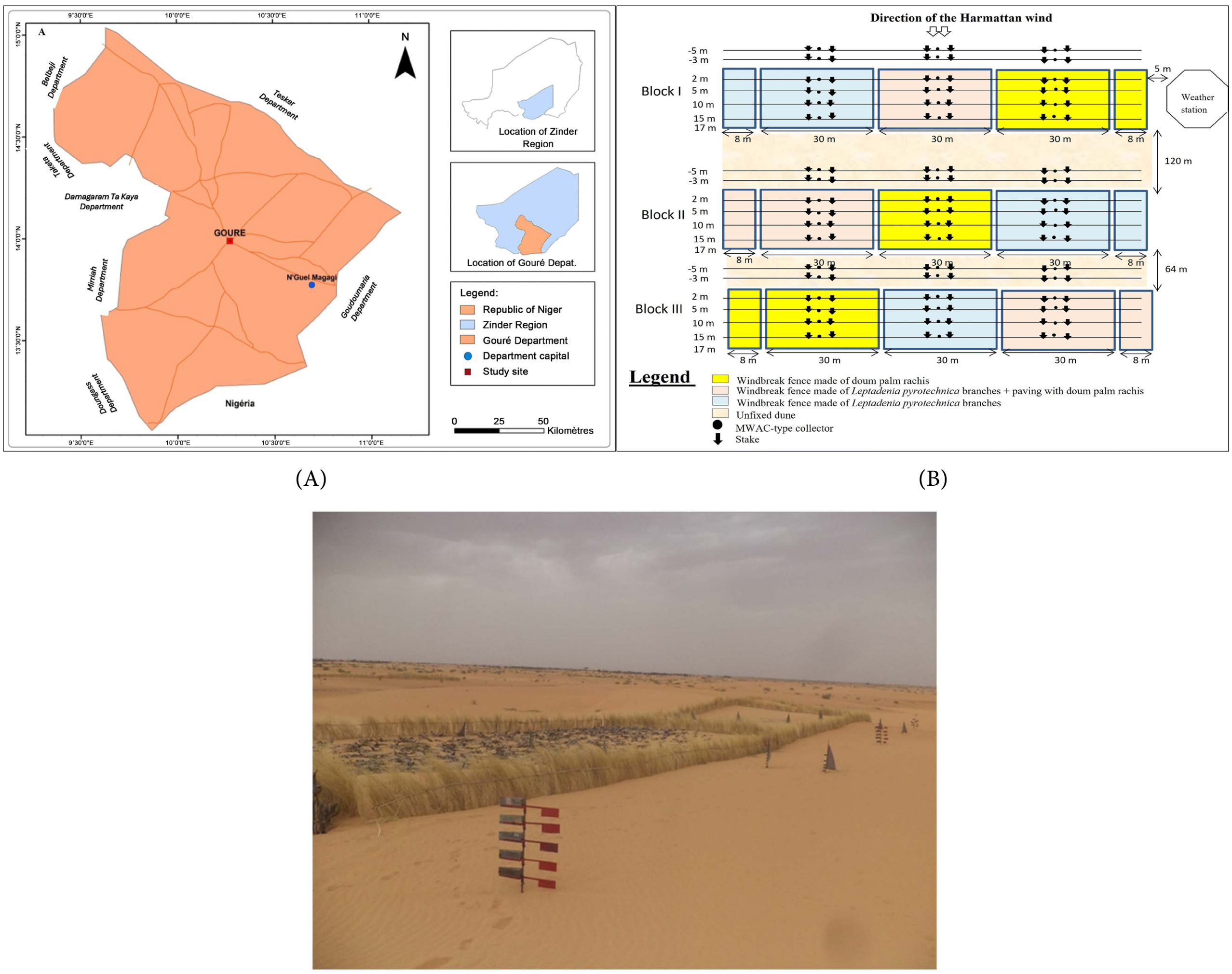
However, despite the widespread use of these materials, scientific knowledge about their actual performance remains limited, both in terms of mechanical sand stabilization and vegetation restoration. Current assessments are mainly based on empirical and scattered observations. Therefore, this study aims to objectively evaluate the effectiveness of the principal materials used for dune fixation with respect to their capacity to stabilize dune systems and promote vegetation recovery.

2. Materials and Methods

The study was conducted on an experimental site located at N'Guel Magagi in the Gouré department, south-east Niger (**Figure 1(A)**). This site consists of an expanse of several active dunes and has never undergone any stabilization.

The methodology used to achieve the aim of the study was to set up an experimental system on this site in order to: 1) characterize the windbreak fence; 2) characterize the wind and rainfall parameters; 3) monitor the topography of the fixed dunes; 4) collect and calculate the aeolian flux; and 5) assess the return of herbaceous vegetation on the fixed dunes over two seasons in 2014 and 2015.

This experimental system (Figure 1(B)) is a Fisher block design comprising three (3) replicates and three (3) treatments. The treatments are: 1) a windbreak fence made of *Leptadenia pyrotechnica* branches arranged as linear hurdles; 2) a windbreak fence made *of Hyphaene thebaica* rachis erected as linear hurdles; and 3) mulch of *Hyphaene thebaica* rachis placed downwind of a linear hurdle of *Leptadenia pyrotechnica*. The dimensions of the windbreak fences are 17 m × 30 m (Figure 1(C)). The windbreak fences are positioned perpendicular to the prevailing harmattan wind direction. At each block, both ends of the windbreak fences are extended by 8 m from the extreme windbreak fence to limit edge effects.



(A) (B)

(C)

Figure 1. Study site: (A) Location of the experimental site; (B) Diagram of the experimental dune fixation setup; (C) A block of the experimental setup in the field at N'Guel Magagi (Gouré/Zinder/Niger).

2.1. Characterization of the Windbreak Fences

The characterization of the windbreak fences consisted of determining: the number and weight of materials used to construct the windbreak fences during their installation, the initial porosity of the windbreak fences after construction, and the variation in the height of the windbreak fences over time.

2.1.1. Number and Weight of Materials Used to Construct the Windbreak Fence

During the installation of the windbreak fences, the following were determined:

- The number of upright branches of *Leptadenia pyrotechnica* per linear meter.
- The number of upright rachis of *Hyphaene thebaica* per linear meter.
- The number of rachis spread per square meter.
- The individual weight of a branch of *Leptadenia pyrotechnica* and/or a rachis of *Hyphaene thebaica*.

Thus, for each block and for the windbreak fences set up linearly, the number of branches and/or rachis was counted for a one-meter linear segment in 30 repetitions (1 one-meter linear segment × 30 repetitions). In total, 90 counts (1 one-meter linear segment × 30 repetitions × 3 blocks) of branches and/or rachis were carried out for the three blocks comprising the experimental setup. The average of these 90 counts is considered.

For the individual weight of a branch of *Leptadenia pyrotechnica* and/or a rachis of *Hyphaene thebaica*, a 25 kg electronic hook scale was used. Ninety branches and/or rachis (30 units per block) were weighed individually. The average of 90 individual weights is considered. The number of paved rachis per m^2 is calculated using Equation (1).

$$\text{Nrachis per square meter} = (\text{Mtrachis}/\text{Prachis})/\text{Splot} \quad (1)$$

where Nrachis per square meter = number of rachis per square meter; Mtrachis = total mass of rachis paved in a plot; Prachis = weight of a single rachis; and Splot = area of the plot (30 m × 17 m).

After the calculation, the average number of rachis per square meter across the three plots for the three blocks was used.

2.1.2. Initial Porosity of the Windbreak Fences

After the construction of the windbreak fences, their initial porosity was assessed using photographs analyzed with the Can-Eye software [20]. This image-processing software, commonly used to estimate leaf area index, enables the detection of bare soil not covered by vegetation. In this study, the stems of *Leptadenia pyrotechnica* and *Hyphaene thebaica* rachis were considered as vegetation. The software was used to determine the area occupied by voids based on images taken perpendicular to the fence surface exposed to the wind. For each type of material, thirty photographs were taken at a height of 50 cm above the ground and 1 m from the fence, covering the height range from 0 to 50 cm, while ensuring that the ground was not visible in the frame. This range corresponds to where most of the aeolian flux is transported [21] [22]. **Figure 2** illustrates examples of photos processed by the Can-Eye software for determining the porosity of windbreaks.

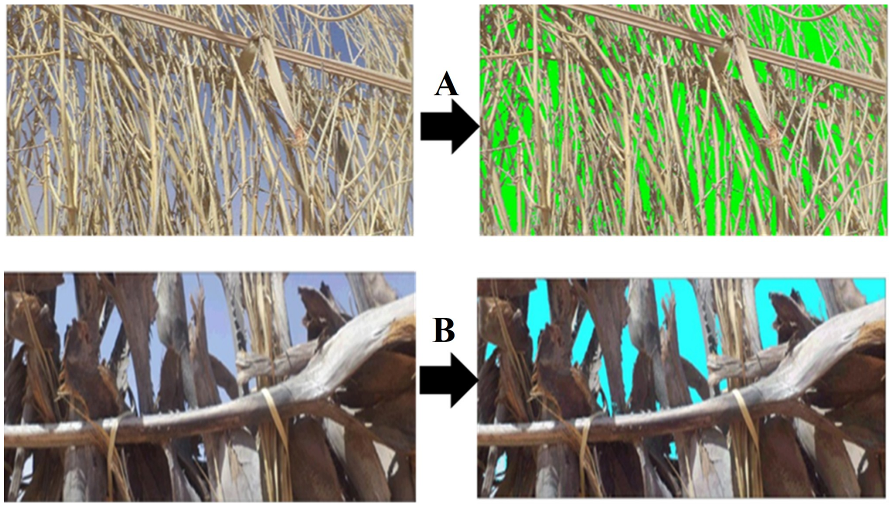


Figure 2. Examples of photos processed with the Can-Eye software for determining the porosity of windbreak fences. (A) Windbreak fence made of *Leptadenia pyrotechnica* branches; (B) Windbreak fence made of *Hyphaene thebaica* rachis.

2.1.3. Variation in the Height of Windbreak Fences Over Time

The variation in the height of the windbreak fence made of *Leptadenia pyrotechnica* over time was measured using a measuring tape. In each plot, thirty measurement points were randomly determined on the windward side of the windbreak fence, and measurements were taken every thirty days from November 21, 2013, to May 20, 2014, for the 2014 season, with an additional measurement on February 13, 2015 (the date of windbreak fence rehabilitation). For the 2015 season, measurements were taken monthly from February 23, 2015, to February 18, 2016.

2.2. Characterization of Wind and Rainfall Parameters at the Study Site

A weather station equipped with a CR10X data acquisition system (Campbell Scientific) was used to monitor wind and rainfall. Sensors included an anemometer (Jean Moren, GME) at 2 m above ground for wind speed, a W200P wind vane at 2 m for wind direction, and a tipping-bucket rain gauge at 1.5 m for precipitation.

2.3. Monitoring the Topography of Stabilized Dunes

The evolution of stabilized dune topography was monitored using stakes along a transect aligned with the windbreak fence's central axis, in the direction of Harmattan winds. Stakes were placed 5 m and 3 m upwind, and 2, 5, 10, and 15 m downwind. Two transects per plot, spaced 5 m apart and each consisting of six stakes, were established. Stake height was measured every 10 days from February to May in 2014 and 2015 to evaluate sand erosion and deposition associated with different winbreak fence materials.

2.4. Collection and Calculation of Aeolian Flux

MWAC ("Modified Wilson and Cooke") sediment traps were used to collect wind-driven sediment flux at different heights. Masts equipped with five MWAC traps set at 9 cm, 19 cm, 29 cm, 44 cm, and 64 cm above the ground were installed along a transect aligned with the central axis of the fences in the direction of the Harmattan winds. These traps were positioned 5 m and 3 m upwind of each fence, and 2 m, 5 m, 10 m, and 15 m downwind. The traps were emptied at regular intervals (every 10 days). The collected sediments were weighed to compute wind sediment fluxes. Flux density (Equation (2)) was obtained by dividing the mass $m(z)$ of trapped sediment by the trap opening area $s(z)$.

$$Q(z) = m(z)/s(z) \tag{2}$$

where $m(z)$ is the mass of sediments trapped in a MWAC and $s(z)$ is its opening surface area.

According to [13] [23]-[26], the flux density is maximum near the ground and follows a power law with height (Equation (3)):

$$Q(z) = a(z+1)^{b} \tag{3}$$

where a is the flux density at $z = 0$ and b is a dimensionless parameter (with $b < 0$).

Integrating the flux density up to a saltation height of 0.635 m gives the cumulative horizontal sediment flux (Fh) expressed in kg·m^{-1} per sampling date (Equation (4)). It represents the amount of sediment transported by saltation and suspension between the surface and 0.635 m height per unit width perpendicular to the wind direction.

$$Fh = \int_{0}^{0.635} Q(z)\,\mathrm{d}z = \frac{a}{b+1}\left[(0.635+1)^{(b+1)} - 1\right] \tag{4}$$

The obtained fluxes were then corrected by the efficiency of the collectors (0.49) [27]. Fh (kg·m^{-1}) represents the proportion of total sediment flux that the device is known to capture.

2.5. Assessment of Herbaceous Vegetation Recovery on Stabilized Dunes

The recovery of herbaceous vegetation was assessed along sections defined along the mast transects. Six bands were delineated as follows:

1) Band 1: between −5 m and −3 m upwind of the windbreak fence.
2) Band 2: between −3 m and the first windbreak fence.
3) Band 3: between the first fence and 2 m downwind.
4) Band 4: between 2 m and 5 m downwind of the first windbreak fence.
5) Band 5: between 5 m and 10 m downwind of the first windbreak fence.
6) Band 6: between 10 m and 15 m downwind of the first windbreak fence.

Two methods were used: the line-point quadrat method of [28], for a systematic inventory of the herbaceous layer in all sections, and [29], the total harvest method to estimate biomass in downwind sections (Sections 3 - 6), where vegetation was abundant. In each section, six 0.5 m^2 plots were randomly placed; all herbaceous species were identified, harvested, and weighed after drying at the end of the rainy season.

2.6. Data Processing

Statistical analyses were conducted on the height of sand deposits generated by the fences and on the dry biomass of each section at the experimental site using SPSS version 20. A multivariate ANOVA was performed to assess the effect of material type on sediment trapping and vegetation recovery. When the ANOVA revealed significant effects, a Tukey post hoc test ($p < 0.05$) was used to compare means. The results of the statistical analyses are presented in tables showing, for each parameter and source of variation, the degrees of freedom (df), mean square, F-value, and associated probability.

3. Results and Discussion

3.1. Characteristics of the Windbreak Fences

Table 1 summarizes the physical characteristics of the windbreak fences constructed from *Leptadenia pyrotechnica* branches, *Hyphaene thebaica* rachis, and their combination. The results reveal a general consistency between 2014 and 2015, suggesting that construction techniques and material properties remained relatively stable over time.

Table 1. Physical characteristics of the windbreak fences.

Materials/Year	P LP/RHT		P LP		P RHT	
	2014	2015	2014	2015	2014	2015
NB, R/m^2	10.1 ± 1.73	10	10.0 ± 1.82	10	29.2 ± 3.57	29
WB, R (g)	658.1 ± 158.6	653.2 ± 162.07	642.5 ± 163.9	647.3 ± 153.7	227.3 ± 84.9	228.1 ± 65.1
NR/m^2	6.24 ± 0.07	6.07 ± 0.24	-	-	-	-
IH (m)	1.70 ± 0.16	1.72 ± 0.63	1.70 ± 0.14	1.71 ± 0.92	1.45 ± 0.15	1.40 ± 3.82
IP (%)	17.6 ± 5.82	19.2 ± 4.45	17.1 ± 6.25	19.6 ± 4.39	15.1 ± 7.45	21.8 ± 5.66

NB, R/m^2: Branches or rachis per meter linear; WB, R (g): Weight of branches or rachises (g); NR/m^2: Number of rachis per square meter; IH(m): Initial height (m); IP (%): Initial porosity (%).

The analysis of Table 1 shows that, on average over the two study years, the construction of one linear meter of a *Leptadenia pyrotechnica* windbreak fence requires approximately 10 branches, each weighing about 650 g ± 6.8 g. In contrast, building a windbreak fence made of *Hyphaene thebaica* rachis requires around 29 rachis, with an average individual weight of 227.7 g ± 0.57 g. Additionally, about six rachis are needed to cover one square meter of surface area.

The average porosity of windbreak fences made from *Leptadenia pyrotechnica* branches and *Hyphaene thebaica* rachis increased from 17% and 15% in 2014 to 19% and 21% in 2015, respectively. This variation can only be attributed to the characteristics of the branches or rachis, as roughly the same number of materials was used to construct the windbreak fences during both measurement seasons. The porosity values observed in 2014 and 2015 can be considered intermediate, falling between low-porosity windbreak fences (almost opaque barriers) and very high-porosity ones. Previous studies have shown that windbreaks with a porosity of 25% - 30% provide better protection [30]. Although the windbreak fences installed at the N'Guel Magagi experimental site exhibit porosities below this range, they are higher than the 9% reported by [18], which nevertheless provided effective protection. Therefore, these windbreak fences meet the standards and should offer acceptable protection.

3.2. Wind Characteristics at the Experimental Site

Figure 3 shows the daily mean wind direction and daily mean wind speed measured at the experimental site. The parameters reflect a typical Sahelian wind regime [13] [31] [32]. Indeed, the mean wind direction exhibits a clear seasonal pattern, highlighting two dominant wind flows: 1) the Northeast Harmattan, a dry and cool wind that may carry dust from the southern Sahara, blowing from November to March, and 2) the Southwest Monsoon, a warm and humid wind blowing from May to September [13] [33].

This pattern has already been documented in the country by several authors [31] [34]-[39].

Daily mean wind speeds do not exhibit pronounced seasonality.

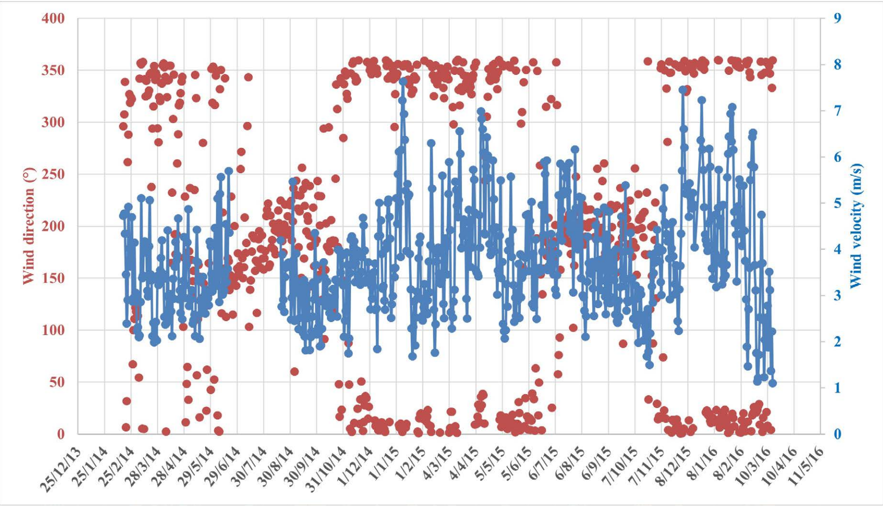


Figure 3. Daily mean wind direction and daily mean wind speed at the N'Guel Magagi experimental site (Gouré) during the experimental period (24/11/2013 to 12/02/2016) (the anemometer was not operational from 01/01/2014 to 15/01/2014 and from 21/06/2014 to 18/08/2014).

The analysis of **Figure 3** shows that few wind speed peaks exceeding the erosion threshold (**Figure 4**) occur mainly during the Harmattan (November-March) and, to a lesser extent, during the Monsoon season (squall lines) and the transitional period (April). As a result, only 16.6% of the recorded wind speeds exceed the threshold velocity.

This observation, consistent with previous studies [13] [31] [32], indicates that daily mean wind speeds generally remain below the saltation threshold for sparsely covered soils (5.6 to 6.05 $m \cdot s^{-1}$ depending on the region in Niger). This is mainly due to the short duration of erosive winds squall lines lasting only 5 to 20 minutes [13] and to the fact that strong Harmattan winds blow predominantly during daytime. Moreover, [40] noted that winds are laminar at night and much more turbulent during the hottest hours of the day, turbulence greatly increasing erosion potential at a given speed.

3.3. Rainfall Characteristics at the Experimental Site

The rainfall parameters assessed at the experimental site, including the number of rainfall events, the annual total rainfall, the average rainfall per event, and the mean interval between rainfall events, are presented in **Table 2**. The data indicate that the number of rainfall events generally ranges from 13 to 14 during the observation period, except in 2013 when it increased to 18. The mean annual rainfall over the four-year monitoring period is 308.75 mm. Additionally, the average rainfall per rainy day is consistently above 10 mm, while the mean interval between two rainfall events exceeds 5 days.

Table 2. Rainfall parameters at the experimental site.

Parameters	Year			
	2013	2014	2015	2016
Number of rainfall events	18	13	14	13
Total rainfall (mm)	272	247	357	359
Average rainfall per rainy day (mm)	15.11 ± 10.26	19 ± 13.71	25.5 ± 19.20	27.61 ± 19.25
Average interval between two rainfall events (days)	6.41 ± 6.10	8.67 ± 7.65	6.61 ± 4.06	5.5 ± 4.21

At the experimental site, rainfall shows strong temporal variability, both within and between years (**Figure 4**) over the monitoring period. July and August are generally the wettest months, except for 2016, when September recorded the highest amount of rainfall.

3.4. Temporal Variation of Windbreak Fence Height and Topographic Variation according to Material Type

Figure 5 illustrates the temporal evolution of windbreak fence height according to the type of material used for dune stabilization over the two measurement seasons.

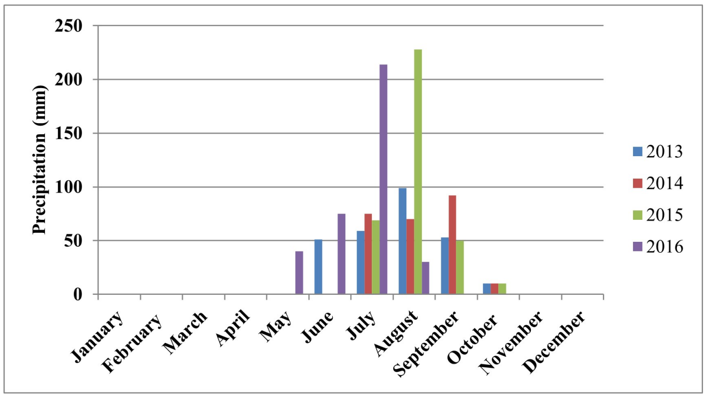


Figure 4. Rainfall variation at the N'Guel Magagi (Gouré) experimental site during the measurement period.

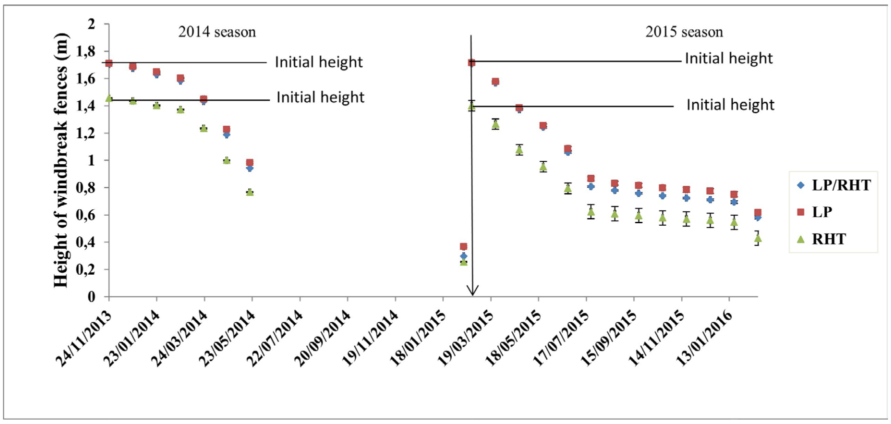


Figure 5. Temporal evolution of windbreak fence height according to the type of material used for dune stabilization (LP/RHT: Windbreak fence made of *Leptadenia pyrotechnica* branches + *Hyphaene thebaica* rachis paving; LP: Windbreak fence made of *Leptadenia pyrotechnica* branches; RHT: Windbreak fence made of *Hyphaene thebaica* rachis), over two seasons: 2014 (24/11/2013 to 13/02/2015) and 2015 (23/02/2015 to 18/02/2016). Error bars represent standard deviations calculated from three values.

The analysis of Figure 5 shows a consistent decrease in windbreak height over time, regardless of the material used. This natural degradation, combined with sediment accumulation around the structures, progressively reduces their sand-trapping efficiency. Similar observations in previous studies [18] [41]-[43] have led to recommendations to periodically raise windbreak height until full site restoration is achieved.

The ANOVA revealed no significant difference between materials in height reduction ($p = 0.993$). However, the decline varies seasonally, with the highest losses occurring during periods of maximum wind erosivity: the Harmattan (February to March), the transitional season (April), and squall line activity (May to July) [13]. Unlike cropland areas where increased vegetation cover limits wind erosion at the onset of the rainy season, degraded dunes in southeastern Niger remain vulnerable year-round whenever wind speed exceeds the transport threshold.

Windbreak fences act as obstacles that influence wind speed, causing the deposition of transported sediments on both sides of the structures. The magnitude of these deposits varies depending on whether they are located on the upwind or downwind side of the first windbreak fence exposed to the Harmattan winds, as illustrated in Figure 6.

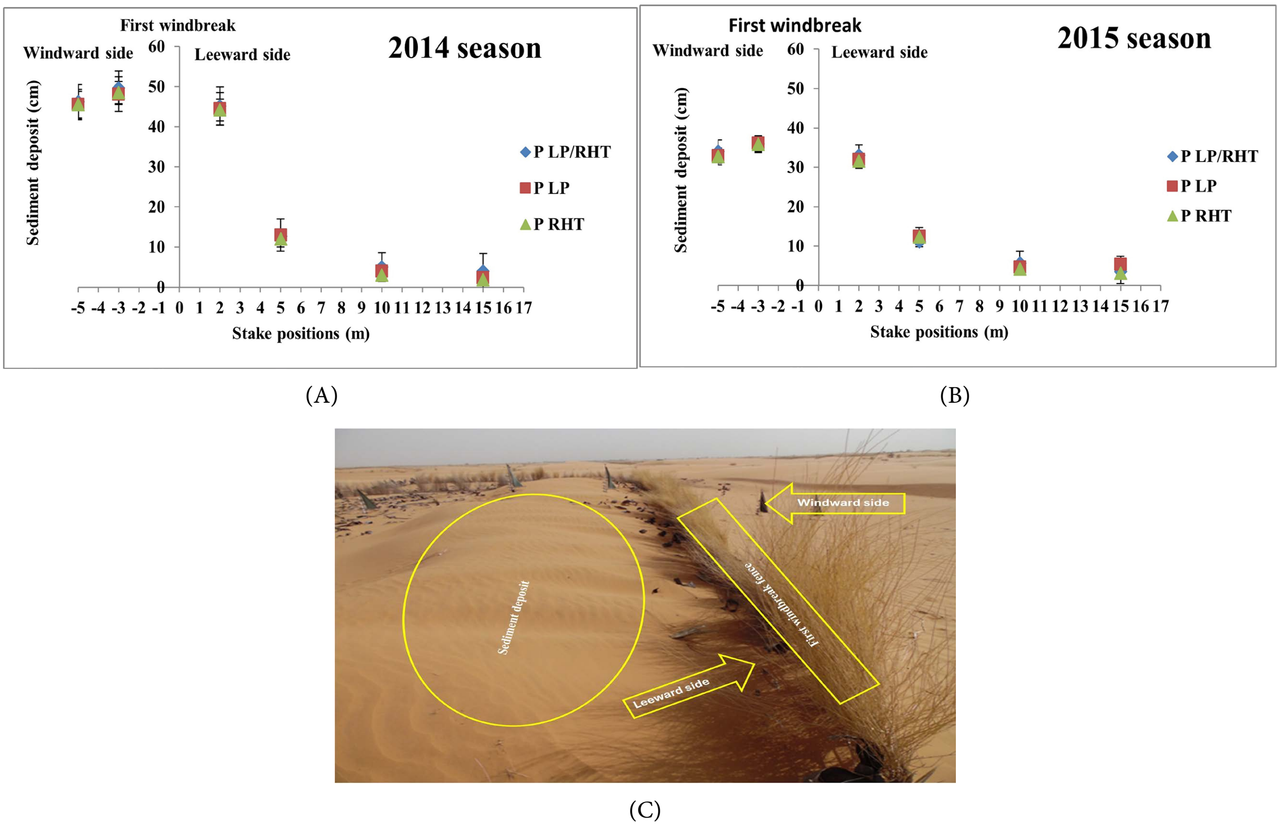


Figure 6. Topographic variation on the upwind and downwind sides of the first windbreak fence of the anti-erosion system at the N'Guel Magagi experimental site (Gouré) for the periods. (A) February 2014 - February 2015 (2014 season); (B) February 2015 - February 2016 (2015 season); (C) Photograph illustrating the on-site conditions.

Analysis of Figure 6 shows that the windbreak fences trap a substantial amount of sediment around them, regardless of the construction material used. Sediment accumulation is highest in the immediate vicinity of the fences (up to 3 m upwind and 2 m downwind), a pattern also reported by [18] in the study area. These findings are consistent with the results of [44], who observed major sand deposition both in front of and behind windbreaks, and those of [45], who noted the formation of small dunes directly downwind of windbreak fences. However, the amount of trapped sediment shows little variation among the different materials tested.

3.5. Variation of Aeolian Flux

The aeolian sediment fluxes collected every ten days, 5 m upwind of the first fence between February and May over two measurement seasons, are shown in Figure 7. In 2014, the flux peaked in February and then gradually decreased until late May, reaching 47.4 kg·m^{-1}. A similar trend was observed in 2015.

During the monitoring period, the mean decadal fluxes were 85.2 kg·m^{-1} in 2014 (from February 24 to May 25) and 94.1 kg·m^{-1} in 2015 (from February 23 to May 24). These values are higher than those reported by [18] in the same region and by [46] in western Niger. [18] recorded about 100 kg·m^{-1} over a one-month period (from January 15 to February 15, 2007) at 3 m upwind, with maximum fluxes in January-February. [46] measured daily fluxes of around 3.7 kg·m^{-1} on a bare cultivated plot during the dry season.

Such discrepancies arise due to 1) spatial and temporal variability in wind characteristics, 2) differences in sampling periods and frequency, and 3) contrasting geomorphological contexts. Earlier studies were conducted either on isolated dunes or agricultural fields where surface roughness (crop residues) partly reduces sand mobility. In contrast, the active dune field of N'Guel Magagi promotes smoother wind flow and stronger transport capacity. [47] also showed that aeolian sediment transport on active dunes peaks in January to April and June to July.

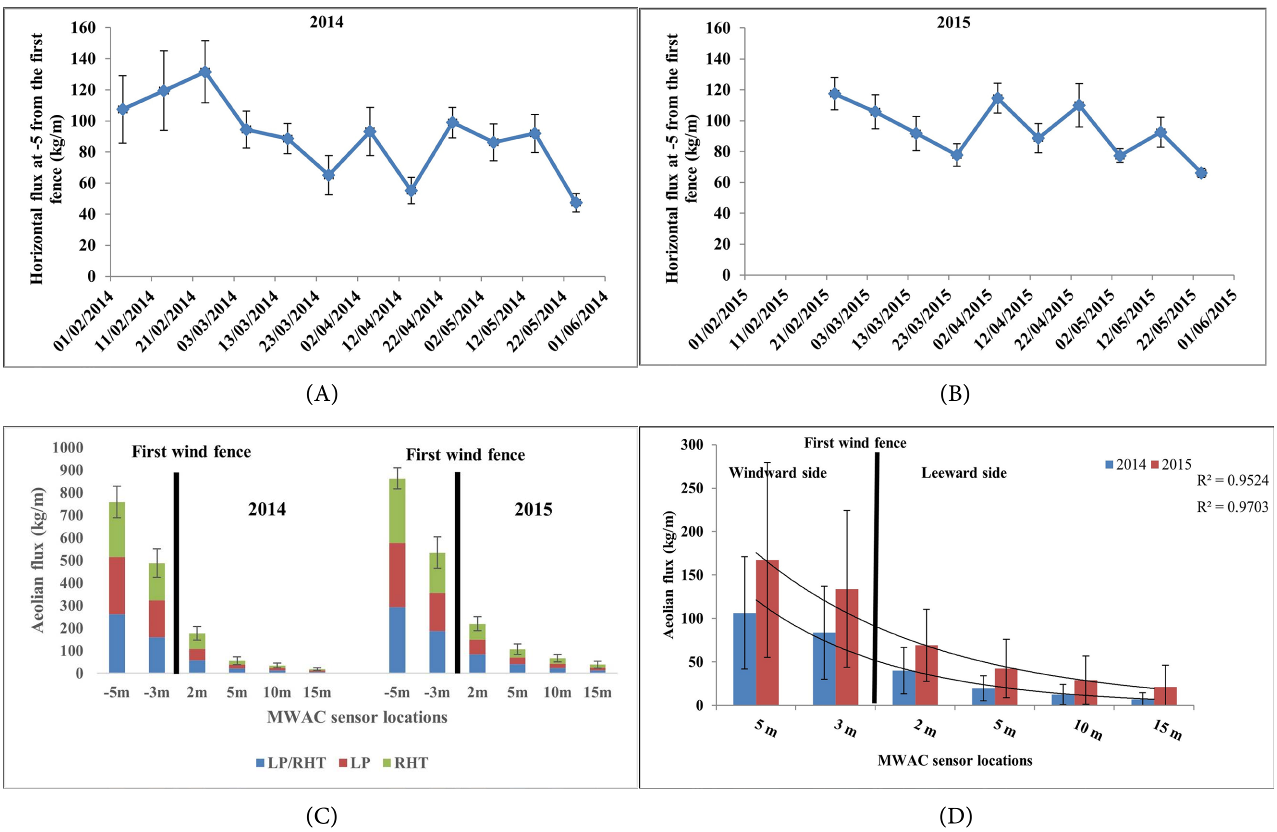


Figure 7. Variation of ten-day mean aeolian flux (kg·m^{-1}): (A) at 5 m upwind of the first windbreak fence in 2014 (February 4, 2014 to May 24, 2014); (B) at 5 m upwind of the first windbreak fences in 2015 (February 23, 2015 to May 25, 2015): (C) based on sensor location and material type, by season for 2014 and 2015, and (D) for all materials combined for both years at the N'Guel Magagi dune stabilization experimental site (Gouré). Error bars represent standard deviations calculated from nine MWAC masts.

Figure 8 shows the cumulative horizontal sediment flux (collected between February and May for the 2014 and 2015 seasons) and the cumulative sediment accumulation (from December 2013 to February 2016) at 5 m upwind of the first windbreak fence.

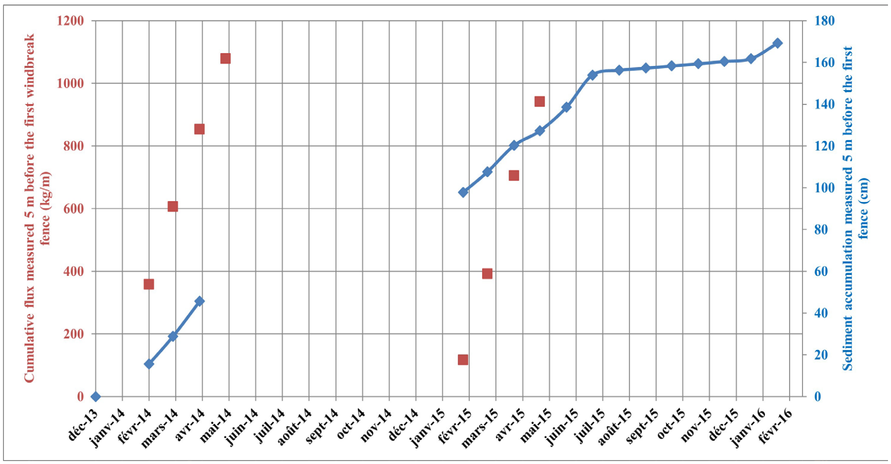


Figure 8. Cumulative horizontal flux and sediment accumulation at 5 m upwind of the first windbreak fence for the entire experimental period. Flux was collected only between February and May. Sediment accumulation was quantified only for the months of February, March, and April in 2014. The measurements are complete for 2015.

For the 2014 season, the total aeolian flux reached approximately 1080 $kg \cdot m^{-1}$, compared to 940 $kg \cdot m^{-1}$ in 2015. This difference can be attributed to changes in the soil surface induced by the installation of the device in 2014. The installation promoted the formation of erosion crusts, which limited the availability of mobilizable particles [46] [48]-[51], and allowed the return of sparse vegetation, adding additional surface roughness [52]. Moreover, the setup led to the formation of an artificial dune near the fences, acting as a counter-dune for the 2015 measurements.

Sand accumulation at −5 m from the first fence reached approximately 170 cm between December 2013 and February 2016. For the 2015 season, two phases can be distinguished: 1) Intense accumulation phase (February to July 2015), with a monthly average of 11.22 cm ± 3.14 cm, like 2014. This period corresponds to strong erosion, occurring at the end of the dry season and the start of the rainy season [13], and 2) Low accumulation phase (August 2015 to January 2016), with a monthly average of 1.30 cm ± 0.51 cm, during which no erosion was recorded on grazed or cultivated plots in other Nigerien regions [31] [46].

This pattern aligns with [47], who noted that erosion on active dunes occurs year-round but diminishes in intensity between August and October.

3.6. Vegetation Characteristics at the Dune Stabilization Site

3.6.1. Herbaceous Biomass Production

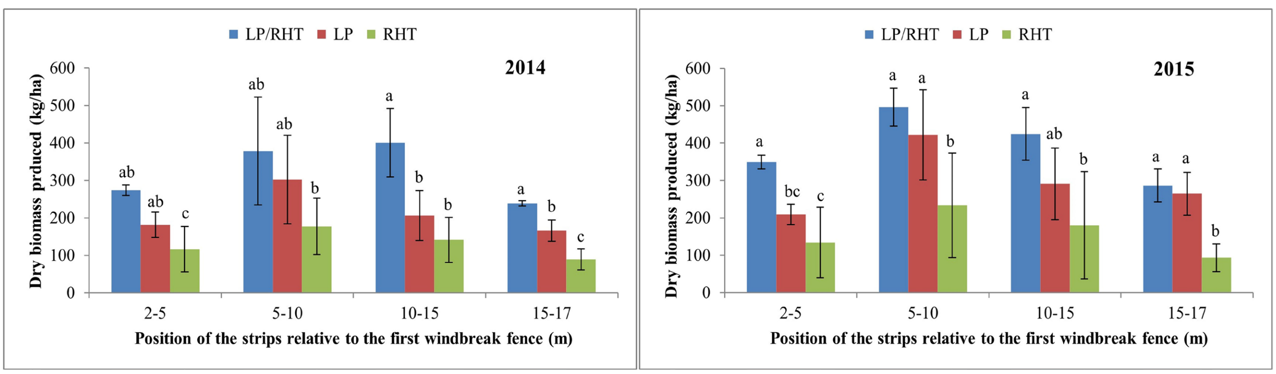
ANOVA results (Table 3) show that dry biomass production is strongly influenced by the type of material used for windbreak fence construction ($p < 0.001$), as well as by the position of the plots relative to the first windbreak fence ($p < 0.001$). In contrast, the interaction between material type and plot position has no significant effect on the dry biomass produced.

Table 3. Results of the analysis of variance for the dry biomass produced per plot at the N'Guel Magagi dune stabilization experimental site.

Source of Variation	Parameters			
	Degrees of Freedom	Mean Square	F-Test	Probability
		2014 Season		
Treatment	2	221.893	20.996	<0.001***
Plot	4	274.600	25.984	<0.001***
Treatment * Plot	8	20.104	1.902	0.097[NS]
Error	30	10.568	-	-
Total	45	-	-	-
		2015 Season		
Treatment	2	318.381	21.673	<0.001***
Plot	4	458.198	31.191	<0.001***
Treatment * Plot	8	26.277	1.789	0.119[NS]
Error	30	14.690	-	-
Total	45	-	-	-

[NS]: not significant; ***: highly significant.

The results of biomass production are presented in Figure 9. Overall, dry biomass production at the stabilized site increases, for all types of materials used and for each year, from the 2 - 5 m zone from the first windbreak fence to the 5 - 10 m zone, where it reaches its maximum, before gradually decreasing toward the 15 - 17 m zone from the windbreak fence.



(A) (B)

Figure 9. Results of the comparison of mean dry biomass produced per band at the N'Guel Magagi dune stabilization experimental site (Gouré), according to the type of material used for stabilization in 2014. Error bars represent standard deviations for three replicates. Means followed by the same letter are not significantly different (p > 0.05).

Analysis of **Figure 9** shows that biomass production progressively increases from the fourth band (2 - 5 m) to the fifth band (5 - 10 m), stabilizes between the fifth and sixth band (10 - 15 m), and decreases in the seventh band (15 - 17 m). Biomass production in the first three bands (first: −3 to −5 m, second: −3 m to the first windbreak fence, third: first windbreak fence to 2 m) is nearly zero. This low production can be explained by disrupted germination due to the accumulation of sand leading to seed scarcity and probable deep burial of seed-containing sediments by wind-blown sand depleted of seeds.

A similar situation was observed by [18], who reported higher herbaceous density in the inner strips of the windbreak fences compared to outer zones directly exposed to Harmattan winds. Likewise, [53] observed that the external strips of the fences lacked conditions favorable for herbaceous seed germination and remained bare

In 2014, the windbreak fence combining *Leptadenia pyrotechnica* and *Hyphaene thebaica* rachis paving (LP/RHT) produced an average of 322.9 $kg \cdot ha^{-1}$ of dry biomass across all plots, compared to 213.98 $kg \cdot ha^{-1}$ for the LP only windbreak fence and 131.19 $kg \cdot ha^{-1}$ for the RHT only windbreak fence. In 2015, these values were 389.22 $kg \cdot ha^{-1}$ for the LP/RHT windbreak fence, 296.58 $kg \cdot ha^{-1}$ for the LP windbreak fence, and 160.25 $kg \cdot ha^{-1}$ for the RHT windbreak fence.

The biomass production within the windbreak fences, regardless of the material type, is due to the significant reduction of wind fluxes, which promotes the trapping of seeds from various plant species [14] [31] [53]. These structures also create a microclimate favorable to seed germination [16] [17]. The higher biomass observed in the LP/RHT fence compared to LP or RHT alone can be attributed to the additional role of paving, which protects the soil surface and/or increases soil cohesion, thereby enhancing surface roughness and the seed-trapping capacity. Furthermore, the rachis mulch improves water retention within the LP/RHT fence, a condition conducive to high biomass production.

3.6.2. Herbaceous Cover and Plant Diversity at the Dune Stabilization Site

Table 4 presents the herbaceous cover and plant diversity parameters at the dune stabilization experimental site.

Table 4. Herbaceous cover and plant diversity parameters at the N'Guel Magagi dune stabilization experimental site.

Materials/Year	P LP/RHT		P LP		P RHT	
	2014	2015	2014	2015	2014	2015
Alpha Diversity	3.63	3.69	3.18	4.56	3.13	3.33
Number of Species	23	24	17	18	13	13
Evenness Index	0.80	0.80	0.78	1.09	0.85	0.90
Simpson Index	0.12	0.12	0.17	0.23	0.16	0.12
Cover (%)	35.06	35.29	21.46	26.38	14.88	17.33

Plant diversity in the stabilized plots varied slightly depending on the type of material used for fence construction. The highest diversity (index of 4.56) was observed in 2015 in the LP plot. Mean herbaceous cover was 35.05% and 35.29% for LP/RHT fences, 21.46% and 26.38% for LP fences, and 14.88% and 17.33% for RHT fences, corresponding to the 2014 and 2015 seasons, respectively. This difference could be explained by the preferential development of a few dominant herbaceous species that are better adapted to the more stable, humid, and sheltered microclimate created by the combined LP/RHT.

These results indicate that the effectiveness of a windbreak fence in terms of herbaceous cover depends on the material used for its construction. Cover was relatively low for RHT and LP windbreak fences compared to LP/RHT windbreak fences.

4. Conclusions

The windbreak fences installed at the N'Guel Magagi experimental site meet technical standards and significantly reduce wind speed. The different materials used for dune stabilization had a similar impact on sand accumulation, particularly in the immediate vicinity of the first windbreak fence exposed to Harmattan winds. Their role in reducing aeolian sediment flux is clearly positive, and no significant differences were observed according to the type of material used.

In addition to reducing sediment flux, the windbreak fences also acted as a barrier, limiting both the loss of soil seed stocks and promoting the trapping of seeds passing through the structure. Regarding herbaceous vegetation restoration, all materials contributed positively, but the windbreak fence combining *Leptadenia pyrotechnica* with *Hyphaene thebaica* rachis paving (a combination of the two main materials) proved more effective than windbreak fences made solely of either material.

In conclusion, all materials used for dune stabilization in southeastern Niger are sufficiently effective to achieve sand stabilization objectives if implementation standards are properly followed. However, the use of the combined LP/RHT method should consider a potential trade-off between its superior performance and the additional costs it may entail, particularly in terms of materials and labor.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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