Scientific Research Publishing

Open Journal of Soil Science, 2025, 15(9), 699-713
https://www.scirp.org/journal/ojss
ISSN Online: 2162-5379
ISSN Print: 2162-5360

Nutrient Transport Associated with Wind Erosion of Sahelian Cultivated Soils: The Case of a Bangou Koiré Millet Field (Southwestern Niger)

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How to cite this paper: Ide, I., Moussa, M.B., Toure, A.A., Rajot, J.L., Adamou, S.N. and Hassane, B. (2025) Nutrient Transport Associated with Wind Erosion of Sahelian Cultivated Soils: The Case of a Bangou Koiré Millet Field (Southwestern Niger). *Open Journal of Soil Science*, **15**, 699-713.
https://doi.org/10.4236/ojss.2025.159031

Received: July 26, 2025
Accepted: September 23, 2025
Published: September 26, 2025

Abstract

Wind erosion is a major environmental problem in the Sahel and other dry regions of the world. It leads to nutrient loss and reduced soil productivity. However, wind transport of nutrients has been poorly studied in the Sahel. The aim of this study is to characterize the seasonal variability of wind transport and determine the associated nutrient losses over an annual cycle. The methodological approach consisted of measuring wind fluxes and determining the levels of physico-chemical parameters in cultivated soils and the fluxes resulting from wind erosion of these same soils. During the monsoon season, between April and September, the fluxes recorded on the millet field represented 97.61% of the annual fluxes, *i.e.*, an average of 7.96 $kg \cdot m^{-1} \cdot d^{-1}$. Only 2.39% of annual fluxes were recorded during the Harmattan, *i.e.*, an average flux of 0.15 $kg \cdot m^{-1} \cdot d^{-1}$. The fluxes contained, respectively, 2 and 1.5 times more fine clay-loam fraction and very fine to fine sands than the contents available in the soil. This is in stark contrast to the skeletal sand fraction, whose soil content tends to increase as a result of wind erosion. As far as nutrients are concerned, wind erosion has resulted in the transport of nitrogen, organic carbon, and phosphorus, on average, 10 times more than is available in the soil. Nutrient transport takes place mainly during the monsoon season, particularly at the beginning, which concerns 49%, 82%, and 60%, respectively, of the annual transport of phosphorus, nitrogen, and organic carbon. In order to protect cultivated soils from degradation, it is therefore imperative to minimize wind erosion of soils at the start of the monsoon season.

Keywords

Millet Field, Wind Erosion, Aeolian Flux, Nutrient Transport, Sahel

1. Introduction

Arid regions cover 40.6% of the Earth's land surface. In 2020, they were home to 30.9% of the world's population, or approximately 2.3 billion people [1]. These environments have been affected by climate change and human pressure for several decades [2]. The Sahel, which, together with the Sahara, constitutes the main dry areas in Africa, has an economy based mainly on the exploitation of natural resources [3]. Indeed, in this area, at least 70% of the population lives in rural areas [4] [5] and depends on subsistence agriculture [6] [7]. The region is highly sensitive to climate variations and is characterized by high rainfall variability [8]-[10]. The particularly severe droughts between 1970 and 1989, for example, led to significant environmental degradation [11] [12]. Thus, they contributed to accentuating the processes of desertification and degradation of cultivated and grazed land [13]-[17].

The Sahel is also an area of high population growth (3.2%) [3] [18]. Niger, for example, has the highest population growth rate (3.9%) in the Sahel [19]. This high rate leads to a doubling of the population every 20 years [20]. The response to the food needs of the rapidly growing Sahelian population is supported by an expansion of cultivated areas [3]. In fact, across the Sahel region, cultivated areas increased by 57% between 1975 and 2000 [21] and by 73% between 1960 and 2010 [22]. In Niger, for example, more than 90% of the potential arable land has already been exploited [21].

Cultivated areas are particularly susceptible to wind erosion [23]-[28]. This erosion carries away soil nutrients and reduces soil fertility [29]. The nutrient content of sandy soils in the Sahel is very low [30], so soil loss through wind erosion could lead to very high nutrient losses in proportion to the available stock and thus contribute to a decline in crop production potential [31] [32]. In the long term, the loss of these nutrient-rich particles reduces soil productivity and water retention capacity through the degradation of soil structure [32]-[34].

Approximately 28% of degraded land worldwide is caused by wind erosion [35], which develops erosion crusts [26] [28] [36] and emits dust following the deflation of the surface horizon [37] [38]. The impact of mineral dust is felt well beyond the areas affected by wind erosion. In fact, in areas of transport and deposition, it causes mineral pollution and the transport of allergens, pathogens, and nutrients [39] [40] and can cause various diseases [41] [42]. However, in all wind flux measurements taken in the Sahel, the transport of associated nutrients has only been determined during a few erosive events, never over a complete cycle. Therefore, this work aims to characterize the dynamics of wind transport over a cultivated Sahelian surface over an annual cycle. Specifically, it aims to: i) characterize the seasonal variability of wind transport and ii) determine the nutrient losses associated with wind transport.

2. Materials and Methods

2.1. Experimental Site

Measurements were conducted near the village of Bangou Koiré (13˚36'3.52"N, 1˚52'44"E), 30 km northwest of Niamey (**Figure 1**). This semi-arid environment is characterized by two types of winds. The monsoon is a wind from the southwest with an average direction of N213˚34˚. It blows mainly between April and September, with maximum daily speeds varying regularly between 8 and 18 $m \cdot s^{-1}$. The harmattan generally begins to blow in October and retreats around March. Its direction is approximately N131˚63˚ and maximum daily speeds are regularly below 8 $m \cdot s^{-1}$ (**Figure 2**). Cumulative annual rainfall is approximately 500 mm between May and September [24].

Measurements were taken in a field cultivated with millet (*Pennisetum glaucum*) (**Figure 3**). The field was cultivated from 2010 to 2018, then left fallow in 2019 before being cultivated again in 2020, mainly with millet combined with beans. Millet is usually sown in pockets in June after the first rain. The millet

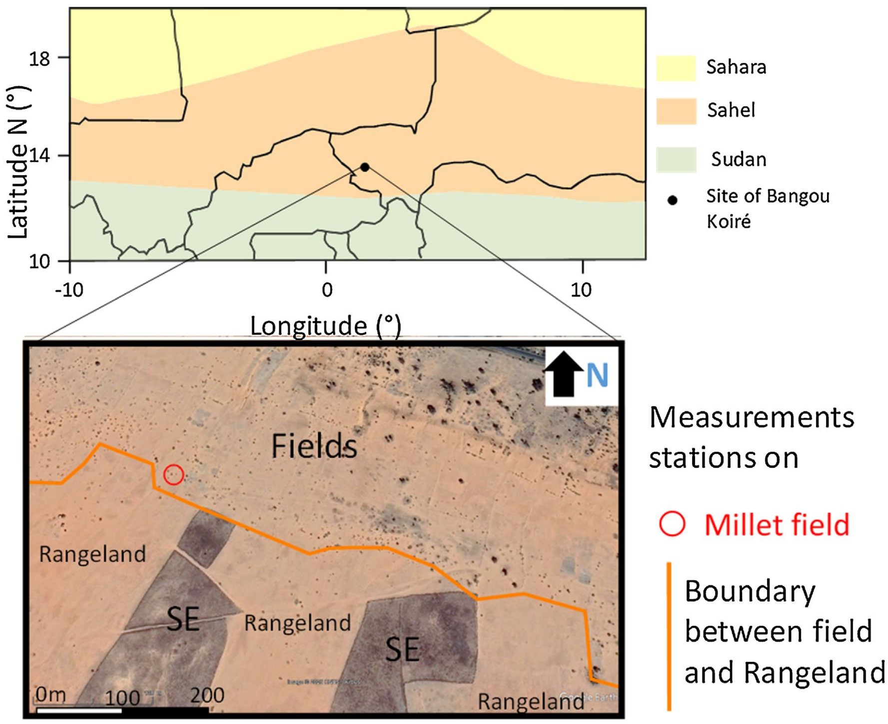

Figure 1. Localization of the study site in the Sahel (top) and land uses around the measurement sites at Bangou Koiré (bottom). SE are anti-erosive layouts of the grassy surface type (Google Earth image, 2019; modified).

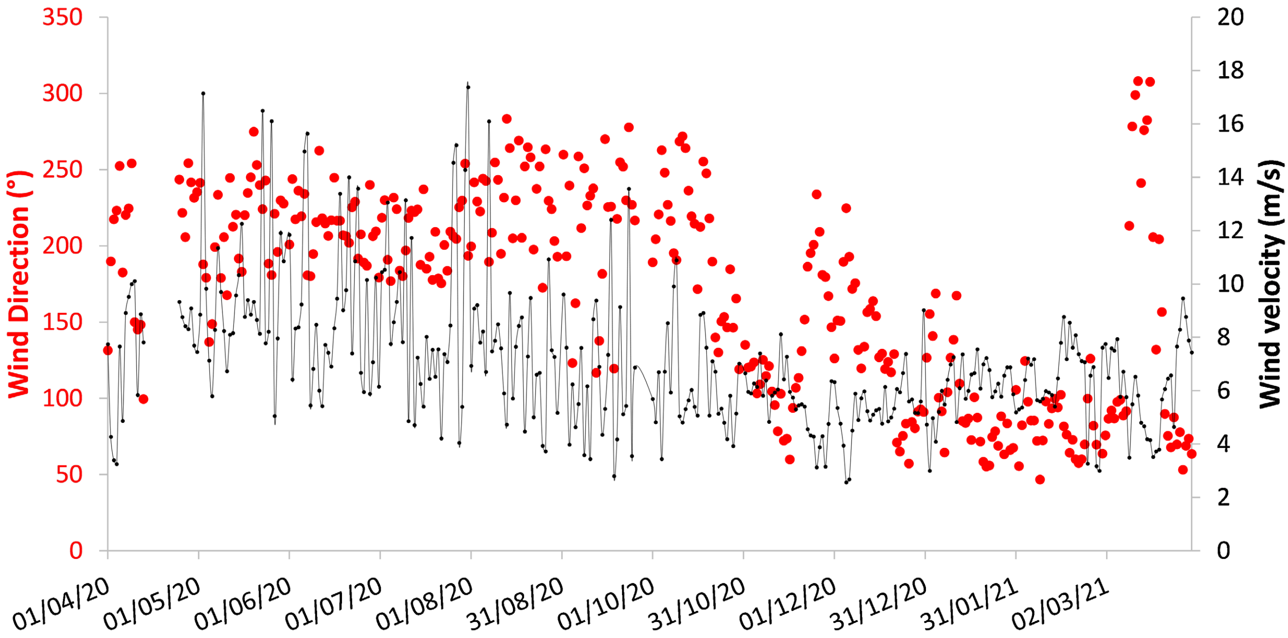

Figure 2. Daily average wind direction and daily maximum speeds (over 5 minutes) measured at 2.5 m above ground level at Bangou Koiré from April 2020 to March 2021. North is 0˚.

Figure 3. Illustrations of vegetation cover in the Bangou Koiré field between 2020 and 2021.

field is then weeded once in July and again in August. The millet ripens and its ears are harvested in September. After the harvest, the field is opened to livestock, which graze on the crop residues. The field surface is then dominated by millet and bean plants, as well as weeds. Vegetation cover gradually increases, reaching its maximum at the end of the rainy season in October. As the stems and leaves of cowpeas are harvested for fodder, the field surface is mainly covered with millet residues during the dry season, which are either lying down or standing up. Soil cover by crop residues has decreased and become very low since February (**Figure 3**).

2.2. Determining the Intensity of Wind Transport

Wind transport over a surface can be defined by horizontal flux. Several authors have measured horizontal flux on different land uses in the Sahel [24] [25] [27] [28] [32] [43]-[46]. Wind transport was determined using BSNE (Big Spring Number Eight) sand traps [47] (**Figure 4**). BSNE traps have been widely used to characterize erosion flux in southern Niger [25]-[28] [32] [48], and China [49]. Three BSNE are installed on a mast at 5, 15, and 30 cm above the ground. Five masts equipped with three BSNE are placed in the millet field, four of which form a 30-meter square, with the fifth placed in the center.

Figure 4. A three BSNE mast installed in the Bangou Koiré millet field: A. side view; B. front view: 1, 2, and 3 are respectively BSNE at the bottom, middle, and high levels above the soil; 4: mast; 5: weathervane.

The measurements were performed over a year, from April 2020 to March 2021. Sediments eroded by wind and trapped in the BSNE were collected every two weeks. Twenty-four collections of sediments were made. The collection interval for eroded sediments represents the main constraint. This constraint does not affect the seasonal or annual cumulative flux but masks the temporal variability. However, it should be noted that a fixed duration for the collection of eroded sediments is common in studies of wind erosion of soils in the Sahel [26] [42].

After every two weeks, the sediments trapped in the BSNE are collected and weighed. A flux density $Q(z)$ ($kg \cdot m^{-2}$) is determined at each BSNE by dividing the mass $m(z)$ of sediments trapped in a BSNE by its opening area $s(z)$ (Equation (1)).

$$Q(z) = m(z)/s(z) \tag{1}$$

The flux density is highest near the ground and follows a power law with the height (Equation (2)) [24]-[28] [31] [32] [50] [51].

$$Q(z) = a(z+1)^b \tag{2}$$

where a is the flux density at height $z = 0$, and b is a dimensionless parameter.

Integrating the flux density over the saltation height set at 0.4 m (Equation (3); [52]) gives the horizontal erosion flux (Fh) expressed in $kg \cdot m^{-1}$ per event.

$$Fh = \int_0^{0.4} Q(z) = \frac{a}{b+1}\left[(0.4+1)^{(b+1)} - 1\right] \tag{3}$$

2.3. Quantification of Nutrients in the Soil of the Millet Field and Transported in Wind Flux

Wind erosion directly affects the top few millimeters of the soil [28]. The soil analysis therefore focused on the surface layer of the field. Thus, five samples were taken from the top 5 centimeters and mixed to form one composite sample representative of the surface soil of the millet field. This composite sample was analyzed in the laboratory of the National Institute of Agronomic Research of Niger (INRAN).

The transport of nutrients in wind flux was determined using the masses trapped in the five BSNE traps at the top of the masts. These masses were grouped together to form a sample to be analyzed per collection of eroded sediments. However, the trapped masses were too small and insufficient to allow analysis for the period from August 2020 to March 2012. That is another constraint linked to the soil analysis techniques used at the INRAN laboratory. So between August and March, the nutrient transport is considered to be nil due to the very small amount of eroded sediments.

The analyses, which concerned both wind flux and soil samples, were carried out at the soil laboratory of the National Institute for Agricultural Research of Niger (INRAN). The parameters analyzed were: 1) carbon content determined by the Walkley and Black method [24] [53] [54]; 2) nitrogen content by the Kjeldahl method [24] [53]; 3) phosphorus content using the Bray method [24] [55]; 4) three granulometric fractions were determined using the Bouyoucos method [24] [56]: mean to very coarse sands, very fine to fine sands, and the clay-silt fraction.

3. Results and Discussion

3.1. Seasonal Variation in Horizontal Fluxes over the Millet Field

Flux measurements are shown in **Figure 5**. The shape of the curve is very similar to those obtained on traditional fields cultivated without organic fertilizer in the Sahel Millet is usually sown in pockets in June after the first rains [23]-[28] [45] [57]. The period between April and July is characterized by intense erosion and corresponds to the start of the monsoon and rainy season. This period of erosion is characterized by the occurrence of very strong wind velocities (**Figure 2**) linked to convective events in a context of minimal protection of the soil surface by crop residues (**Figure 3**). Between April and July, the fluxes recorded on the millet field, with an average of 11.94 $kg \cdot m^{-1} \cdot d^{-1}$, represented 93.28% of the annual fluxes. Only 2.39% of the annual flux was recorded during the Harmattan, representing an average flux of 0.15 $kg \cdot m^{-1} \cdot d^{-1}$, compared to 97.61% during the monsoon (**Table 1**). This confirms that wind transport is mainly active at the beginning of the monsoon on cultivated areas in the Sahel.

The annual flux was 1 468 $kg \cdot m^{-1}$, while in Kilakina (South-east Niger), which records 200 mm less rainfall than Bangou Koiré, the maximum annual flux was 2 900 $kg \cdot m^{-1}$ on a millet field [25], *i.e.* twice that of Bangou Koiré. In Banizoumbou, under similar rainfall conditions between 1996 and 1998, a maximum cumulative total of 601 kg·m^{-1} was measured, while [27] measured 370 kg·m^{-1} between 2006 and 2008, which are respectively 2 and 4 times lower than in Bangou Koiré. In fact, the cultivated soils at Banizoumbou had greater vegetation cover than at Bangou Koiré. With these annual horizontal fluxes, soil losses of 20 T·ha^{-1}·yr^{-1} were recorded on the Banizoumbou field [27]. Soil losses on the millet field in Bougou Koiré, where flux can reach four times those of the Banizoumbou fields, could therefore be well above 20 T·ha^{-1}·yr^{-1}.

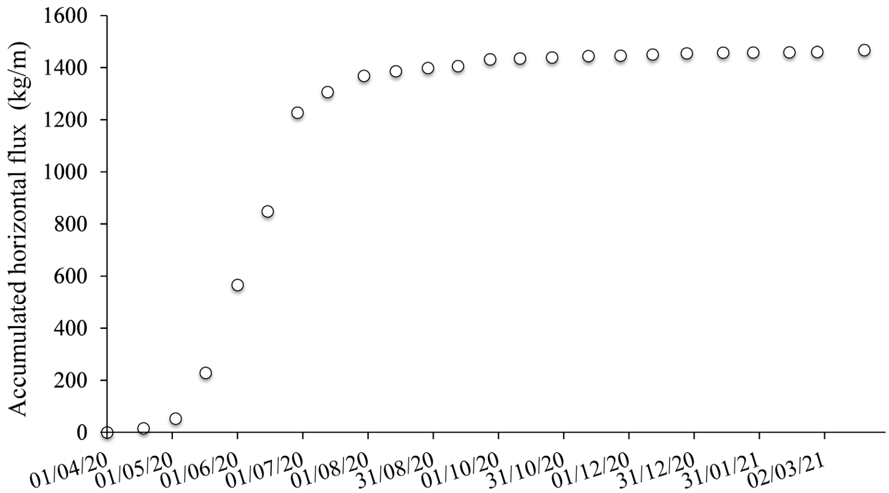

Figure 5. Intra-annual dynamics of horizontal flux measured at Bangou Koiré on the millet field from April 2020 to March 2021.

Table 1. Comparison of seasonal horizontal flux measured on the millet field between 2019 and 2021.

Periods	Seasons	Accumulated horizontal flux (kg/m)
2020-2021	Monsoon	1432.62
	Harmattan	35.011

3.2. Grain Size Fractionation Due to Wind Erosion of Soils in the Millet Field

Figure 6 and **Table 2** show the comparative distributions of particle size fractions of soil and wind-flux sediments generated by erosion on the same soil. This comparison shows that the content of fine particles (clay and silt) is higher in wind-flux sediments than in soil. In fact, the fine fraction (clay and silt) and fine sand contents are 6.16% and 50.63%, respectively, in the soil. In the flux, these contents are 12.46% and 76.16%, respectively, *i.e.*, more than 2 and 1.5 times higher than the content available in the soil.

Wind erosion has therefore led to granulometric fractionation by transporting and most likely depleting the soil of fine particles. Granulometric fractionation, although less intense than that observed in Bangou Koiré due to wind erosion, has been observed in studies carried out in Niger [49], and China [50]. [58], for example, showed that on cultivated soils on the Ordos Plateau (China), wind erosion depletes the soil of erodible particles with diameters between 60 and 400 µm. Similarly, [59] used wind tunnel measurements to show that increased wind flux causes significant entrainment of particles and aggregates with diameters of less than 100 µm. Losses of fine particles could lead to nutrient losses and reduce the productivity of Sahelian soils. The nutrient content of Sahelian soils is known to be low and concentrated in the surface horizon, which is subject to wind erosion [23] [31] [32].

Contrary to our measurements at Bangou Koiré, [58] has highlighted an increase in the fine clay-silt fraction of soils due to wind erosion. It should be noted that the very high wind flux (**Figure 5**) at Bangou Koiré could indicate significant saltation, which could have released and consequently transported more fine particles.

The measurements have shown that fluxes contained less coarse sand than the available content in the soil (**Figure 6**). In fact, the coarse sand content in the soil was four times higher than in the fluxes. There was therefore less coarse sand in the fluxes measured. In fact, the weight of coarse particles is such that they are transported close to the soil surface, where crop residues no doubt trap them more effectively. Wind erosion of the millet field surface therefore tends to increase the sandy skeletal fraction in soils, making them more unreactive and poorer.

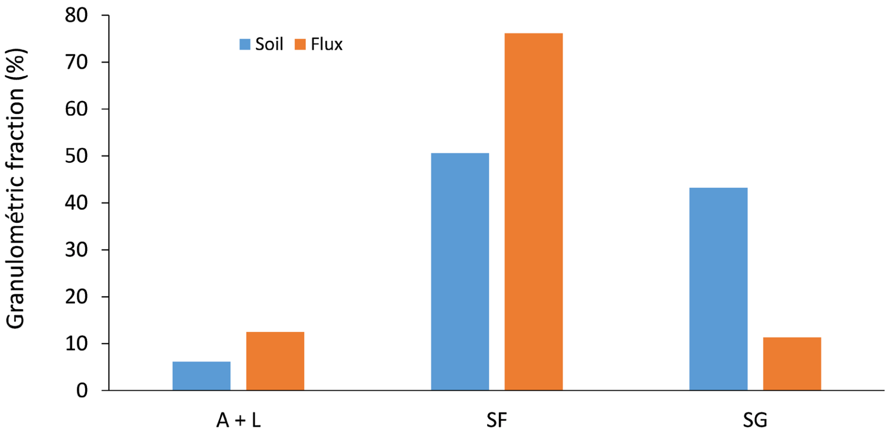

Figure 6. Comparison of particle size fractions determined in annual flux and in millet field soil.

Table 2. Distribution of particle size fractions between the flux and the soil of the millet field.

Land uses	Samples	Particle size fraction (%)			
		A	L	SF	SG
Millet fied	Soil	4.01	2.15	50.63	43.21
	Flux	6.71	5.77	76.16	11.36

3.3. Biochemical Fractionation Due to Wind Erosion of Millet Field Soils

Figure 7 and **Table 3** show the concentrations of fertilizers transported in wind flux and those available in millet field soils. It appears that the nitrogen, organic carbon, and phosphorus contents in the flux are, on average, 10 times higher in wind flux than in soils (**Table 3**). The nitrogen, organic carbon, and phosphorus contents in the soil are 0.634%, 0.1%, and 33.57 ppm, respectively. In the flux, these contents are 3.064%, 1.71%, and 260 ppm, respectively, which are more than 5, 17, and 8 times higher than the available content in the soil.

At the village level in the Sahelian environment, [56] have shown that nutrient loss through wind erosion is higher than that caused by water erosion. Nutrient losses from a field during an event of wind erosion can represent up to 73% of the nitrogen and 100% of the phosphorus needed for plant production [60]. [61] also showed that soil losses during just two erosion events resulted in losses of 18.3 and 6.1 $kg \cdot ha^{-1}$ of nitrogen and phosphorus, respectively.

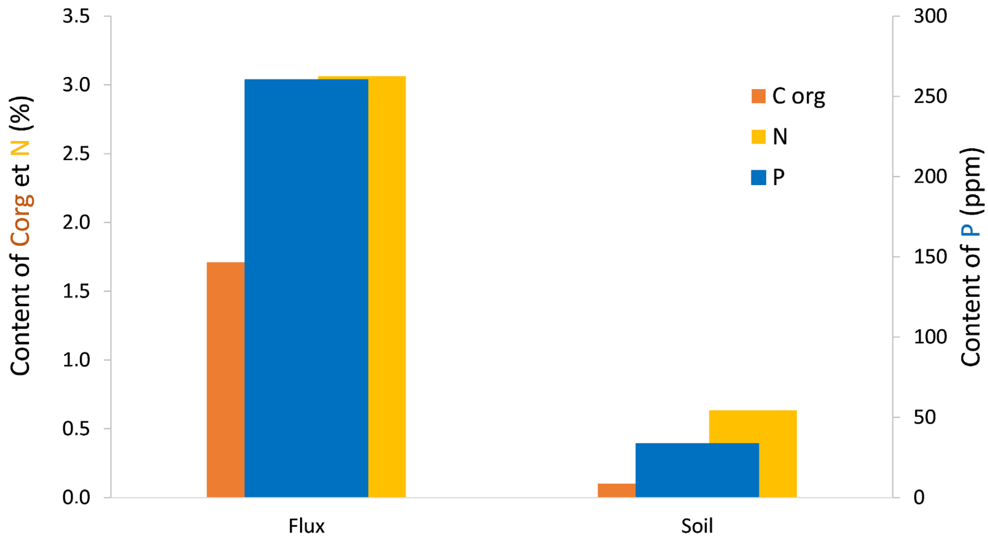

Figure 7. Distribution of fertilizer contents (N, C org, and P) in the annual flux and in the soil of the millet field.

Table 3. Fertilizer contents (N, C org, and P) and their comparative ratios in the annual flux and the millet field soil.

Nutrients	Millet field		
	Soil	**flux**	**flux/soil**
N (%)	0.634	3.064	4.83
C org (%)	0.1	1.71	17.10
P (ppm)	33.57	260.4	7.76

3.4. Seasonal Dynamics of Nutrient Transport in Millet Fields

Nutrient transport showed significant seasonal variability (**Figure 8**; **Table 4**). There appears to be a period of intense transport between April and July, which corresponds to the beginning of the monsoon and rainy season. This period of high nutrient mobilization can be explained by the occurrence of very strong winds (Figure 2) and minimal protection of the soil surface by vegetation (Figure 3). During this period (April–July), all nutrient transport takes place on the millet field. However, the period from April to May was very characteristic. This period generated 49%, 82%, and 60% of the annual transport of phosphorus, nitrogen, and organic carbon, respectively, on the millet field, for only 21% of the horizontal flux mobilized on the field.

During the second part of the monsoon (August to September) and throughout the Harmattan, nutrient transport is practically non-existent on the millet field. Indeed, during this period, wind erosion on the field was low, with only 2.39% of the annual flux recorded.

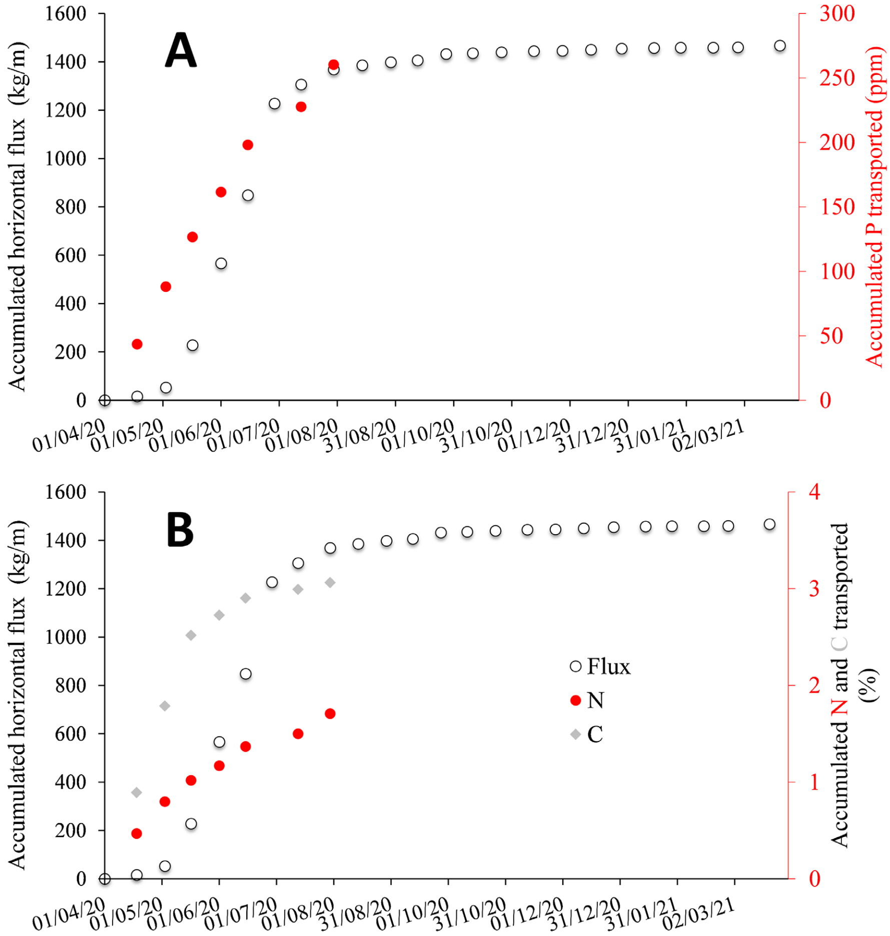

Figure 8. Comparative trends in horizontal fluxes and associated nutrients: A. phosphorus, B. carbon, and nitrogen on the millet field during the wind erosion cycle 2020-2021.

Table 4. Seasonal variation of fertilizer contents (N, C org, and P) transported in the horizontal flux of the millet field.

Period	Seasons	N (%)	C (%)	P (ppm)
2020-2021	Monsoon	3.064	1.71	260.39
	Harmattan	~0	~0	~0

4. Conclusions

The objective of this study was to characterize the seasonal variability of sediment and associated nutrient transports due to wind erosion of a cultivated sandy surface in the Sahel. Wind flux follows a distinct seasonal pattern. The millet field was eroded particularly during the monsoon season, when 97.61% of annual flux is recorded. Wind transport is especially intense at the beginning of the monsoon season (April-June), during which 93.25% of annual flux is generated, representing an average flux of 11.94 $kg \cdot m^{-1} \cdot d^{-1}$. During the Harmattan (November-March), the wind erosion flux averaged 0.15 $kg \cdot m^{-1} \cdot d^{-1}$ and represented 2.39% of the annual total.

Wind erosion has led to granulometric, chemical, and biochemical fractionation. In fact, it transported 2 and 1.5 times more fine clay-loam and very fine to fine sand than is available in the soil. On the other hand, it enriched the soil with coarse sand, the content of which was 4 times lower in the flux than in the soil. With regard to chemical and biochemical fractionation, it was found that wind erosion causes the transport of nitrogen, organic carbon, and phosphorus at rates 4.83, 17.1, and 7.76 times higher than those available in the soil of the millet field. Nutrient transport occurs mainly during the monsoon season and was particularly significant between April and May. In order to preserve the quality and fertility of Sahelian cultivated soils, which are highly susceptible to wind erosion, it is therefore imperative to minimize this erosion at the beginning of the monsoon season.

Acknowledgements

This work was supported by the IMPATERS (IMpacts de la PATure sur l'ERosion éolienne au Sahel) and FARSIT Project GEPAAP (ÉCOSYSTÈMES DES LACS MERIDIONAUX AU NIGER: Géodynamique, Erosion, Pollution, Agriculture et Autonomisation des Populations).

Conflicts of Interest

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

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