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Impact of very low crop residues cover on wind erosion in the Sahel

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ABSTRACT

In the Sahel, with average annual precipitation in the order of 500 mm yr^{-1} , wind erosion occurs mainly on cultivated millet fields whose surfaces are only partially covered by crop residues. The impact of these residues on wind erosion was not clearly established. The objective of this study is thus to quantify the actual amount of crop residues in traditional Sahelian fields and to determine their impacts on wind erosion by reference to a bare surface throughout the seasonal cycle over several years.

At the beginning of the year during dry season, Sahelian farmers use to “clean” their fields, i.e. cut and lay flat on the soil surface any millet stalks still standing and yearly sprouts of shrubs. After this clearing, the crop residues cover (CRC) regularly decreases passing from 12% to less than 2% four months later. On traditional cultivated plot, crop residues efficiently prevent soil losses by wind erosion during the dry season and considerably reduce erosion fluxes at the beginning of the rainy season. However, for CRC lower than 2%, wind velocities were sufficient to produce important erosion even during dry season. A minimal cover rate of about 2% (100 kg ha^{-1}) thus appears as critical to reduce wind erosion. This reduction is driven by the higher aerodynamic roughness length which increases the wind erosion threshold velocity. If field clearing is made in January, as currently done, the CRC just after clearing should be about 800 kg ha^{-1} to maintain CRC above 2% at beginning of the rainy season when wind velocities are the highest and wind erosion the most intense. Our results also demonstrate that during the second part of rainy season wind erosion is reduced, not so much due to vegetation development but rather to a decrease in the number and the intensity of high winds events.

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1. Introduction

In the Sahel, about 75% of the population lives in rural zones (United Nations, 2007) and depends on subsistence agriculture (Sivakumar, 1989). The region is characterized by a continuous degradation of soil structure by wind erosion (Lamers, 1998). Wind erosion is the main cause of sediment losses on cultivated sandy soils (Rajot, 2001), i.e. the soil were develops the Sahelian staple crops. Sahelian farmers perceive wind erosion as a vicious circle that originates in the decline in soil fertility and plant coverage (Sterk et al., 1998; Biielders et al., 2001). In Niger, for example, farmers are aware that wind erosion is a major problem for the production of

millet, the major crop of the region (Biielders et al., 2004). Wind erosion removes and redistributes fine soil particles, which contain the largest amount of nutrients for plants. Nutrient content in sandy soils, the most abundant in the Sahel, is very low (Bationo et al., 2000). As a consequence, surface soil loss by wind erosion may cause extremely important nutrients loss and could significantly contribute to the decline in crop productivity (Sterk and Raats, 1996; Biielders et al., 2002). For example, Sterk and Stein (1997) quantified the soil loss associated to two erosion events to 38 Mg ha^{-1} , including 57.1 kg ha^{-1} of potassium, 77.6 kg ha^{-1} of carbon, 18.3 kg ha^{-1} of nitrogen, and 6.1 kg ha^{-1} of phosphorus. On the long term, soil structure degradation and loss of nutrient-rich soil particles can reduce soil productivity and water retention capacity (Biielders et al., 2002; Gomes et al., 2003; Visser et al., 2005a). Wind erosion is therefore a challenging issue for agriculture development in the Sahel region where population growing rate is the highest in the world.

The primary functional units in a number of Sahelian cultivated zones are still composed of cultivated fields and of fallow lands. In the Sahel, fallows are not bare surfaces since natural vegetation is allowed to grow. Natural vegetation protects the surface from wind erosion

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and allows an efficient trapping of sediments eroded from neighboring fields (Rajot, 2001; Bielders et al., 2002). On the opposite, cultivated fields are submitted to intense wind erosion (Sterk and Stein, 1997; Sterk and Spaan, 1997; Rajot, 2001; Bielders et al., 2002). The most common explanation for field wind erosion is the fact the field surfaces are not sufficiently protected by vegetation. However, field surfaces are not completely bare, but are partially covered by crop residues. The effects of crop residues have been widely studied to develop wind erosion reduction techniques. Such studies are mainly derived from measurements on experimental plots and with controlled crop residues amounts. They have shown that crop residues efficiently trap saltating particles (Geiger et al., 1992; Bielders et al., 2000). This effect of crop residues is well known by Sahelian farmers who use it to restore soil productivity on small degraded spots within their fields (Lamers, 1995; Lamers and Feil, 1995; Sterk et al., 1998; Léonard and Rajot, 2001).

However, the influence of residues amount on wind erosion has not been properly established and quantified in Sahelian conditions. Many studies demonstrate that residues amount higher than or equal to 1500 kg ha⁻¹ leads to an important reduction of wind erosion (Michels et al., 1995a; Sterk and Spaan, 1997; Bielders et al., 2000). The effect of smaller quantities of residues on wind erosion is not so clear. Michels et al. (1995a) did not observe further reduction in horizontal flux density for crop residues amount of 500 kg ha⁻¹. Sterk and Spaan (1997) even observed an increase in erosion rate caused by the strongest winds for residues quantities of 1000 kg ha⁻¹. These authors also stated that a crop residue amount of 1500 kg ha⁻¹ cannot be achieved in Sahelian fields without substantial external support, which is generally not compatible with the current cultural practices and resources in the region.

The present study was conducted on traditional cultivated fields, i.e. in conditions representative of the quantities and distribution of crop residues that are actually observed in the studied zone. The objective of this study is to quantify the amount of crop residues in traditional fields and to determine its impact on wind erosion throughout the seasonal cycle, by monitoring the erosion flux and crop residues amount over several years.

2. Materials and methods

2.1. Traditional field management

Cultivated soils in Niger are extremely sandy (Gavaud, 1977), with more than 90% of sand in the first centimeters (Rajot et al., 2003), and generally classified as Psammentic (Soil Survey Staff, 1975) or Cambic Arenosols (ISSS et al., 1994). The surface does not exhibit any gravel or clods that could affect its roughness. As a result, surface roughness is essentially controlled by the annual crop cycle and linked to the climatic cycle. In Niger, as in the majority of Sahelian countries, millet is the staple food crop. Millet is planted at the end of the dry season just before the beginning of the rainy season or in the three days following the first intense rainfall.

Millet is sown in "pockets", small holes inferior to 15 cm deep, dug with a hand hoe at a distance of at least 1 m each other. Weeding is carried out with an "iler", a long shallow cultivating hoe that cuts the soil 2–5 cm under the surface. Similar cultivation practices are performed throughout the Sahel where millet is cultivated on sandy soil (McIntire et al., 1989). During the rainy season, pearl millet develops in fields following precipitation. Maximum growth is reached by the end of the rainy season (end of September or early October). Once vegetation has hit maximal growth, the harvest season begins. After this period, millet stalks are left erect in fields and are partially consumed by animals or collected by farmers for building material. In the months of December and January, fields are cleared: any millet stalks still standing and yearly sprouts of shrubs are cut and laid flat on the soil surface.

2.2. Studied plots

The studied plots are located close to Banizoumbou (13.54°N; 2.66°E), a Nigerien village located approximately 60 km east of Niamey. A number of wind erosion studies have already been conducted in this area since the mid-1990s (Bielders et al., 2000; Rajot, 2001; Bielders et al., 2002; Rajot et al., 2003). The present work has been conducted in the framework of the African Monsoon Multidisciplinary Analysis international project (Redelsperger et al., 2006). In this context, several studies on mineral dust emissions by Aeolian erosion have been conducted on the site during intensive observation periods (Rajot et al., 2008; Sow et al., 2009). Dust concentrations are also monitored since 2006 at the regional scale (Marticorena et al., 2010).

Since June 2005, two rectangular plots of 100 × 150 m² have been instrumented to monitor the aeolian activity (Fig. 1). These plots were surrounded by non-cultivated bands of 20 m length where natural fallow-type vegetation has grown. These vegetation bands isolated the plots from sediment flux coming from the surrounding fields. Indeed, Bielders et al. (2002) showed that ~90% of sediment flux entering such vegetated surface deposits in the first 20 m. During the year 2005, the non-cultivated bands have been prepared by refraining from weeding, thus encouraging the development of natural typical fallow-land weeds and shrubs. The two plots were treated the same manner during this year, i.e. traditionally cultivated. Specific treatments for the two experimental plots started after April 6, 2006. One plot, referred to as PA hereafter, was completely stripped from crop residues and maintained bare by weeding, harvesting, and the suppression of all forms of vegetation since this time. The second plot, PB, has been cultivated by traditional methods: farmers determine by their own knowledge and experience when to clear the field, to sow, weed, and harvest. These four actions remain the basis of cultural practices in the region.

2.3. Horizontal flux measurement

Horizontal or saltation flux was monitored using three Big Spring Number Eight sand traps (BSNE) (Fryrear, 1986) mounted on poles at heights of about 5, 15, and 35 cm, i.e. in the saltation layer. The two highest BSNEs on the pole have an opening of 10 cm². The lowest has a smaller opening (2 cm²) to prevent the sampler from overloading since the flux is highest close to the soil surface. The deployment of the BSNEs was the same on the two plots PA and PB: 25 poles of 3 BSNEs were installed following south-west alignments on the borders of the plots and inside the plots (Fig. 1). This positioning was optimized regarding the dominant wind direction for wind erosion in Western Niger (Michels et al., 1995a).

After each erosion event, the sediments caught in the BSNEs were collected and weighed. If rain occurred after an erosion phase, sediments were oven-dried at 60 °C for three days before weighing. The exact heights of the BSNE openings have been controlled at each pole below the BSNEs as a function of their orientation after each erosion event using a graduated ruler, in order to account for possible variations in local micro-topography.

For each erosion event, the flux density $Q(z)$ (kg m⁻²) (z being the height of the centre of the opening) was determined for each BSNE by assuming a 100% efficiency of the sand-traps as demonstrated by Goossens et al. (2000). The flux density is obtained by dividing the collected mass of sediment, $M(z)$, by the surface of the opening $s(z)$.

$$Q(z) = M(z) / s(z) \quad (1)$$

Flux density is maximum at the soil surface and follows an exponential decrease as a function of height (Fryrear et al., 1991; Stout and Zobeck, 1996; Sterk and Raats, 1996)

$$Q(z) = a(z + 1)^b \quad (2)$$

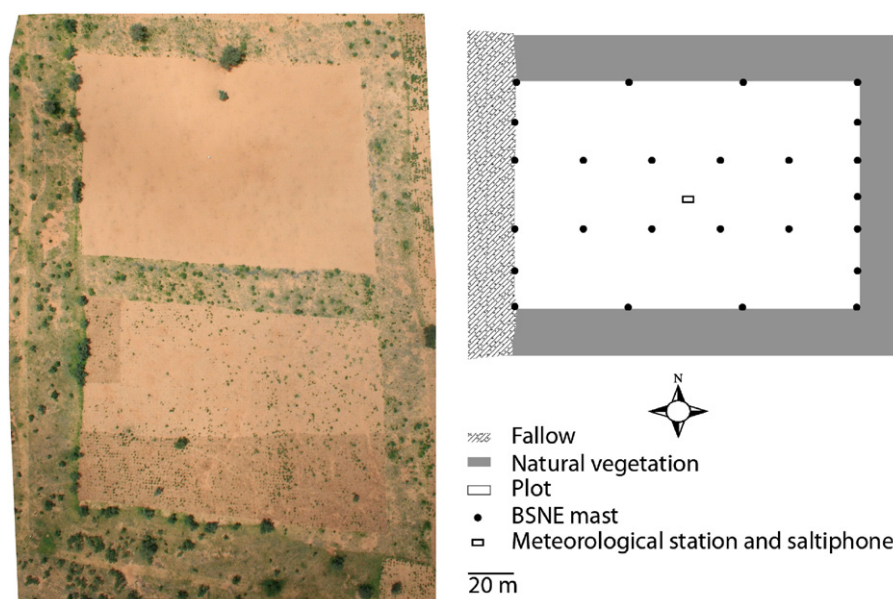


Fig. 1. Aerial photograph of plot PA (top) and PB (bottom) on the 29th of August 2006. Note that the plot PB was under weeding in its south part. In the right, schematic diagram of instruments and sand traps layout at each plot. Mean erosive wind direction is from the East.

where a is the flux density at a height of $z=0$ and b is a non-dimensional parameter.

The horizontal flux of erosion (F_h) corresponds to the amount of sediment mass crossing a section of unit length perpendicular to the wind over the total duration of an erosive event. It is computed by vertical integration of the flux density in the saltation layer up to 0.4 m (Rajot et al., 2003).

$$F_h = \int_0^{0.4} Q(z) = \frac{a}{b+1} (0.4 + 1)^{(b+1)} - 1 \quad (3)$$

in kg m^{-1} per erosion event.

2.4. Dynamic parameters

2.4.1. Meteorological parameters

Masts equipped with 4 anemometers (Campbell A 100R) have been implanted in the middle of plots to calculate the aerodynamic roughness length (Z_0) (see Section 2.4.2). In 2005, only one mast was used, on plot PA, since the same treatment was applied to the two plots. From March 2006 an additional similar mast has been installed in the middle of plot PB. It was set up 1.5 months before PA stripping to check that the 2 plots had the same aerodynamic roughness before treatment and to study the roughness change due to surface modification. On the masts, the anemometers were placed respectively at 0.35 m, 0.70 m, 1.40 m, and 2.50 m from the ground. Wind speeds (in m s^{-1}) were measured every 10 s, averaged over 5 min and stored in data loggers (Campbell CR10X). Wind direction was measured by a 2D sonic anemometer (Windsonic Gill Instrument Ltd) in the dust monitoring station (Marticorena et al., 2010) located 200 m from the plots. As for wind speeds, wind direction was measured once every 10 s, but only the 5 min average was stored in the data logger (CR200 Campbell©). Rain was monitored at the same place, using a tipping bucket rain gauge (ARG100 Tipping Bucket Raingauge Campbell©).

2.4.2. Aerodynamic roughness length (Z_0)

Aerodynamic roughness length Z_0 can be derived from the vertical wind speed profile (Zobeck et al., 2003). Theoretically, it corresponds to the height at which wind speed becomes zero (Stull, 1991). This measurement is a proxy of the geometric roughness of land and is a

good indicator of soil erodibility (Blumberg and Greeley, 1993). Indeed, erosion threshold tends to increase when the aerodynamic roughness length increases (Marticorena and Bergametti, 1995). As a result, for high roughness lengths, only very strong winds can produce erosion.

Aerodynamic roughness length was computed for each plot from Eq. (4) using a minimum of three points in the wind speed profile. For plot B, it was only assessed until millet attained a height of 0.7 m. In the absence of a temperature profile, the calculation is made by assuming dynamic neutrality. To minimize the effects of thermal instability of the atmosphere on the wind profile, and to obtain data for wind speeds at which mechanical turbulence exceeded buoyancy effects (Lancaster and Baas, 1998), the calculation is made only for relatively high winds i.e. for wind speed at 0.35 m higher than 2.5 m s^{-1} .

$$U(z) = (U^* / k) \times \ln(z / Z_0) \quad (4)$$

where $U(z)$ (m s^{-1}) is the average wind speed at a height of z (m), U^* (m s^{-1}) is the friction wind speed and k ($=0.4$) is the Von Karman constant.

This equation is fitted on the measured wind speeds to determine Z_0 and U^* (e.g. Zobeck et al., 2003). A daily median value is calculated from all measurements available each day.

2.4.3. Threshold wind speed

Theoretically, the erosion threshold speed corresponds to wind speed at which the first sand grains start moving on the surface. Soils grains having the optimum size for wind erosion, and thus the minimum threshold wind speed, have diameters of the order of 60–100 μm (Chepil and Woodruff, 1963).

The threshold wind speed of erosion is difficult to measure in the field. It is commonly achieved by using sensors of piezzo-electric or acoustic design such as the Sensit or the Saltiphone (Van Pelt et al., 2009). In this study, each plot was equipped with a Saltiphone (Spaan and van den Abeele, 1991) located in the centre of the plot at 7 cm above the ground, which register particle impacts accumulated over 10 s. Saltation sensors are generally considered as not enough sensitive to detect the impacts from small sand particles, i.e. in the range of 60–100 μm , especially at relatively low wind speeds that correspond to the erosion threshold. As an example, Van Pelt et al. (2009) showed that the saltiphones are not able to register the

impacts of sand grains with diameter of 150 μm for wind speeds of 7.5 m s^{-1} . In addition, because of its design, this sensor cannot be placed at the ground surface. Therefore, they are theoretically unable to register the movements of sand particles first moving at the surface.

As a proxy of the erosion threshold, we thus defined a threshold speed based on measurements of the saltiphones that record the impact of larger sand grains. This allows, at least comparing the sensitivity to wind erosion of the two types of studied surfaces.

This threshold speed is calculated over a one-month period. The number of impacts recorded in 10 s is accumulated during the same time period than the wind speed record, i.e. over 5 min. Saltation records during rainfall events are not taken into account, since the impact of rain drops disturb the measurements. In addition, measurements taken during the 24-hour period following rainfall were not taken into account in order to avoid the influence of the soil humidity on the saltation threshold speed.

To determine the threshold, classes of wind speeds (measured at 2.50 m) of 0.2 m s^{-1} width are defined. P_i , the probability of saltation occurrence for each wind speed class, is given by:

$$P_i = (n_i / N_i) \times 100 \quad (5)$$

where n_i is the number of 5-minute periods in class 'i' during which saltation occurred (counts > 1 cts/5 mn) and N_i is the total number of 5-minute periods in class 'i'. The threshold is thus defined as the class of wind speed with the probability of saltation occurrence of 50% (Fig. 2).

2.5. Crop residue measurements

During the rainy season, vegetation in Sahelian fields consists mainly of pearl millet (*Pennisetum glaucum*). Traditionally, millet plants are regularly distributed, with an average distance of about 1 m between the plants. During the rainy season and thus the millet growing phase, the heights of sixty millet plants were measured each week in various locations on the plot. In the dry season, field biomass is mainly made of crop residues, including the stems and stumps of millet stalks. Weeds are also present, as well as some debris from wood. These crop residues are heterogeneously spread out on the field surfaces. To measure as precisely as possible the temporal evolution of the crop field coverage, two characteristics are measured, the Crop Residue Density and the Crop Residue Cover.

2.5.1. Crop residue density

The Crop Residue Density (CRD) is defined as the mass of crop residues per unit surface on the field. To account for the heterogeneity of the crop residues distribution at the field scale, measurements were

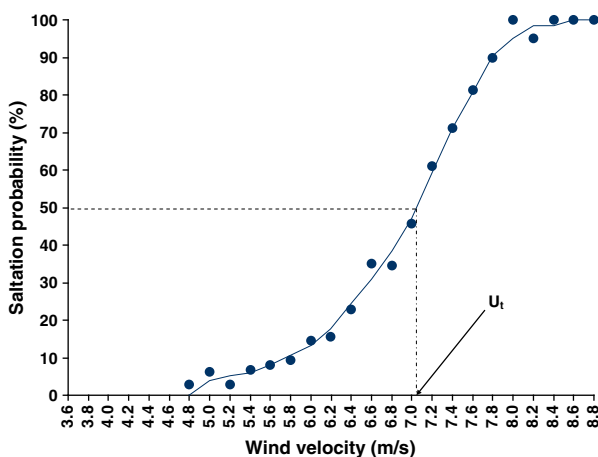


Fig. 2. Example of threshold wind speed computation (U_t).

performed on 36 homogeneous rectangular plots of 12 m^2 area (4 m \times 3 m) covering the full range of densities observed in traditional millet fields. A photograph of each plot was taken before the collection of crop residues. The collected crop residues were oven-dried at 80 $^\circ\text{C}$ for three days and then weighed with a balance (Denver instrument XP-3000, precision = ± 0.1 g) at the laboratory. The CRD, expressed in kg ha^{-1} , is obtained by dividing the dry mass M of the residues by the plot area, A .

$$\text{CRD} = M / A \quad (6)$$

Millet stumps and roots that were completely buried in the field have not been collected and thus not included to determine the CRD since they do not affect the surface roughness.

2.5.2. Crop residue cover

The Crop Residue Cover (CRC) is defined as to the proportion of surface covered by crop residues on a reference surface (expressed in %). The CRC is determined using photographs taken regularly at the same places since 2006. Ten reference surfaces of 12 m^2 (4 m \times 3 m) have been selected on each plot, 20 cm east of the BSNE poles installed inside the plots PA and PB (Fig. 1). The photographs are taken with a digital camera (Canon EOS 350) 6 m above the surface. A preliminary treatment with Adobe Photoshop allows to correct for the perspective and to scale the images to actual dimensions of the reference surfaces. The photographs (900 \times 1200 pixels) are then analyzed using a software (ImageJ) that allows to identify and count the pixels with crop residues and the pixels of bare soil. The CRC is computed as the ratio of crop residues pixels to the total number of pixels.

3. Results and discussion

3.1. Climatology: Wind direction, wind speed, and rain

The average daily wind direction (Fig. 3) presents a well-marked seasonal cycle, typical of the two main Sahelian trade winds systems (e.g. Mainguet and Chemin, 1978; Karimoune, 1994; Sivakumar and Michels, 1996; Ozer, 2001) : the Harmattan, a dry wind from the north-east blows from November to March while the Monsoon a humid south-western flow prevails between May and September (Fig. 3). This seasonal shift in the wind directions is due to the seasonal displacement of the Inter-Tropical Convergence Zone (ITCZ). April and October are transitional months characterized by unstable wind direction passing from north-east to south-west and vice versa.

The first rains occur in the Monsoon season, generally after the end of May, when convection starts to develop in the Monsoon layer. Rains become more frequent and intense after mid-July and until the end of August (Lebel et al., 1997; Lebel and Ali, 2009). They are essentially

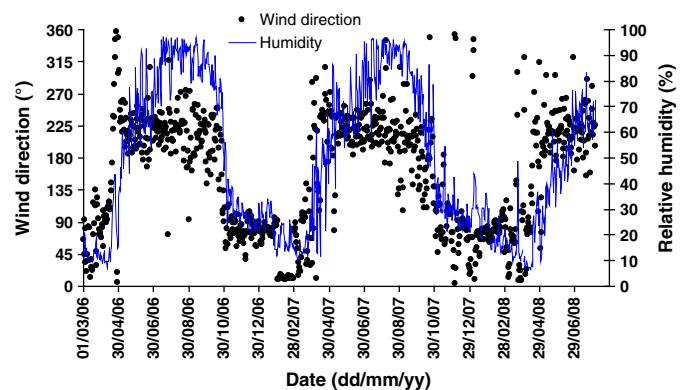


Fig. 3. Seasonal variation of the averaged daily wind direction and the relative humidity. The changes in wind direction and relative humidity allow for the identification of the Harmattan period and Monsoon period.

produced by Mesoscale Convective System (MCS) that rapidly moves across the Sahel from east to west (D'Amato and Lebel, 1998). Ahead of these systems, extremely high wind speeds are responsible for sudden and intense erosion events of very short duration (10 to 30 min).

Wind speeds do not present a seasonal dynamic as marked as wind direction or wind humidity, as already discussed by Marticorena et al. (2010). Daily average wind speeds rarely exceed 5 m s^{-1} at 2.5 m on the cultivated surfaces. The maximum daily average of 5 min wind speed is regularly higher than 7 m s^{-1} , and the strongest wind speeds occur mostly at the beginning of the Monsoon season from May to mid-July (Fig. 4). As described above, these strong winds generally correspond to the passage of convective events.

3.2. Dynamics of wind erosion

Wind erosion fluxes have been monitored for more than three years on the two experimental plots. Two periods are distinguished in the analysis of the experimental data: before and after the stripping of the plot PA, on April 6, 2006. Since this date, the surface of PA has been maintained bare while PB has been cultivated in the traditional manner every year.

3.2.1. Erosion dynamics before the stripping of PA

From June 10, 2005 to April 6, 2006, plots PA and PB were traditionally cultivated in the same manner. The aerodynamic roughness length, Z_0 , derived from the wind profile measurements in March and April 2006, is identical on the two plots, confirming that they had the same surface state (Fig. 5A). Eighteen erosive events were recorded during this period. Flux measurements were also identical on the two plots (Fig. 5B). From these results we assume that the two plots show similar behavior against wind erosion and that comparison will therefore be possible after the treatment of PA.

3.2.2. Erosion dynamics after the treatment of PA

3.2.2.1. Dynamics of vegetation on the cultivated field surface (PB).

The typical seasonal cycle of millet growth in 2006 is illustrated on Fig. 6. In 2006, sowing took place on the 15th of May at the very end of dry season. Millet started to develop after the first significant rainfall occurring on the 1st of June (11.8 mm) and progressively increased to reach a maximum at the end of September. Harvest took place just after this maximum by the beginning of October. The temporal evolution of the millet's height is very similar to the temporal evolution of the cumulated precipitation, with a time shift of about one month. This illustrates how much water availability controls vegetation growth in the Sahel.

The CRC was monitored after clearing on plot PB. The evolution of the CRC relative to the date of clearing is illustrated on Fig. 7. CRC on the field is maximum just after the clearing and decreased

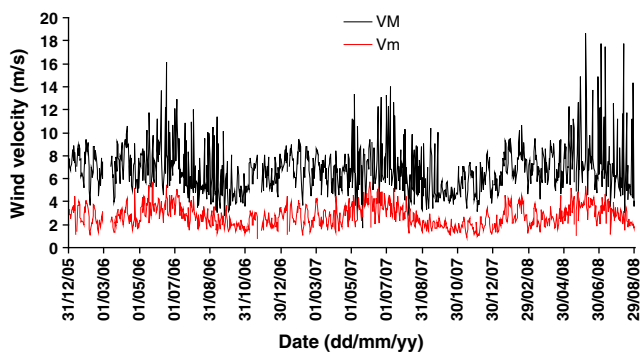


Fig. 4. Seasonal variation of maximum wind speeds (VM) averaged over 5 min and daily mean wind speed (Vm) measured at 2.5 m height.

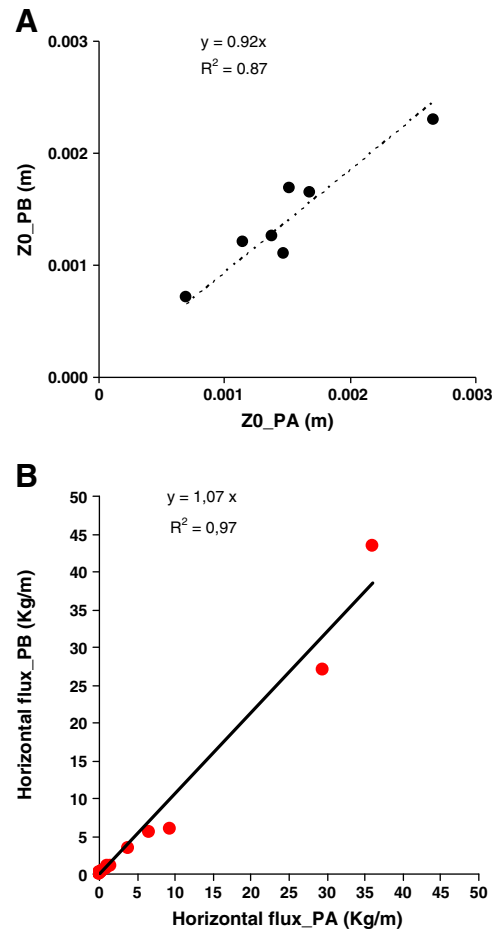


Fig. 5. Comparison of A: the aerodynamic roughness length (Z_0) and B: average horizontal flux measured on plots PA and PB before the stripping of PA.

exponentially from the 12% measured ten days after clearing to less than 2% four months later. This reduction in total cover is due to a number of factors, including the burying of the residues by trapping sediments, the consumption by livestock, the use as combustible or building material, and the consumption by termites. Reduction of crop residues occurs more rapidly just after the clearing when millet leaves, which are easily degradable and more frequently consumed by livestock than straw, are still available at the surface.

CRC and CRD appear as significantly correlated ($R=0.95$) (Fig. 8). This high correlation makes possible the estimation of the CRD from the undisturbed measurements of CRC on plot PB.

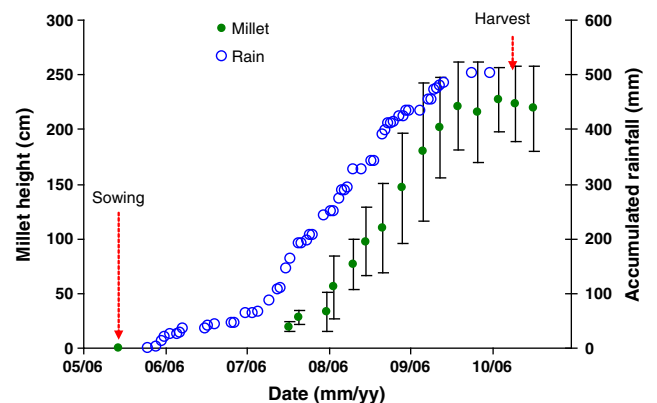


Fig. 6. Monitoring of millet plant height and accumulated rainfall depth for the 2006 season.

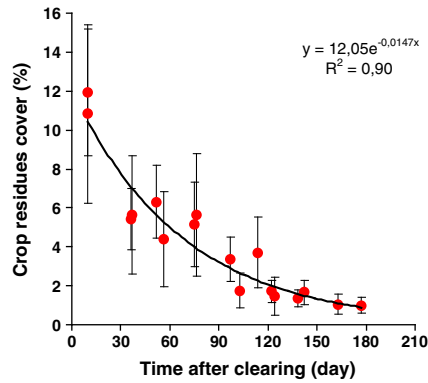


Fig. 7. Evolution of the total Crop Residue Cover (CRC) with standard deviation after the clearing of PB for the three cropping years.

The highest CRC, measured just after clearing, corresponds to CRD around 800 kg ha^{-1} . For a period of 13 consecutive years in the same area, [Hiernaux et al. \(2009\)](#) measured the total production in millet straw and weeds in 24 non-manured farmer fields and found that it does not exceed an average of 1500 kg ha^{-1} . Our value of 800 kg ha^{-1} was obtained four months after the date at which the outputs were estimated in the above-mentioned study i.e. after first setting apart of straw by farmers for building and by livestock for feeding. These two results are very consistent and confirm that the CRD in our study are representative of the current amount in traditional farmer fields. It must be noted that the CRD estimated at the end of the dry season, in such traditional non-manured fields is very low, around 100 kg ha^{-1} . This is 5 times lower than the lowest crop residue densities tested in wind erosion study by [Michels et al. \(1995a\)](#), for example.

3.2.2.2. Relationship between the vegetative cycle and aerodynamic roughness (Z_0). After PA stripping, Z_0 became very different on the two plots ([Fig. 9](#)). Compared to plot PB, Z_0 dramatically decreased on PA, and randomly fluctuated between 10^{-4} m and 10^{-5} m without any temporal variability. On the opposite, on plot PB, Z_0 ranged from 10^{-3} m to 10^{-2} m with a seasonal cycle linked to the crop and climate cycle. This cycle can be described by a two-phase cycle: 1) from the clearing of the field until July, the value of Z_0 is small and fluctuates, but presents a decreasing trend with a sudden jump around April, 2) from the end of July, it starts to increase. The April jump during phase 1 corresponds to the change in wind direction ([Fig. 3](#)) that marks the initiation of the Monsoon flow. This variation of Z_0 as a function of the wind direction can be explained by the heterogeneity of the roughness and topography of the field surfaces. Such a variation of Z_0 is well known in Nigerien fields ([Rajot et al., 2003](#); [Sow et al., 2009](#)) and has already been observed on cultivated fields, for example in semi-arid South Tunisia [Kardous \(2005\)](#). During phase 1, Z_0 is essentially controlled by crop residues that constitute

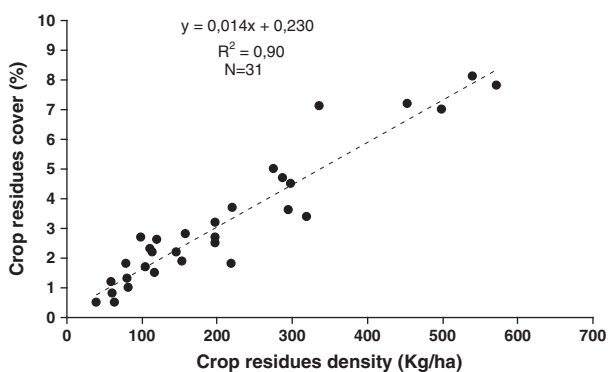


Fig. 8. Correlation between crop residues density and the Crop Residue Cover (CRC).

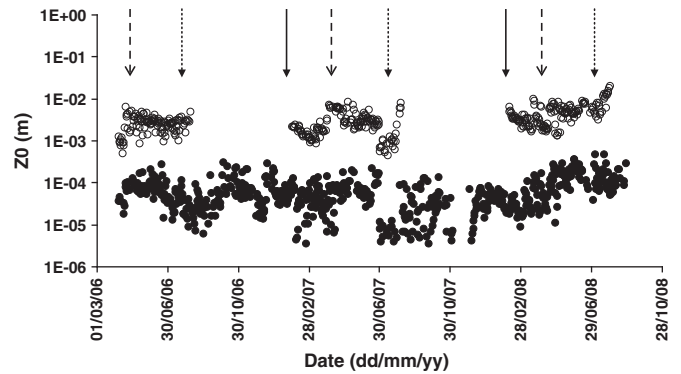


Fig. 9. Evolution of the aerodynamic roughness length Z_0 on PB (open circle) and PA after stripping treatment (full circle). Dashed arrows indicate the change in wind direction, solid arrows indicate the clearing of PB and dotted arrows indicate the beginning of Z_0 increase due to crop growth. Note that on PB, aerodynamic roughness was only assessed until millet attained a height of 0.7 m.

the main covering of field surfaces after clearing. The increase in Z_0 by the beginning of August (phase 2) can be attributed to the growth of millet plants ([Fig. 6](#)). The evolution of the Z_0 in this study is similar to that measured by [Bielders et al. \(2004\)](#) on a traditional millet field.

Z_0 dynamics all along the year illustrated on [Fig. 9](#) include measurements for all wind directions. Some directions may biased estimation of Z_0 by a too short distance between measurement point and the borders of the plot where natural vegetation was allowed to grow. By selecting Z_0 measurements obtained for wind directions corresponding to the largest distance between plot borders and the plot centre, where Z_0 was measured ($232^\circ \pm 6^\circ$), Z_0 become much less variable on plot PB. When focusing on the wind erosion period i.e. after field clearing, a linear decrease of Z_0 is observed as a function of time ([Fig. 10](#)). This decrease can be explained by the decline in crop residues cover described above ([Fig. 7](#)). The linear regression between Z_0 and time was used to retrieve the Z_0 value corresponding to the date when CRC was measured on PB. [Fig. 11](#) is obtained by plotting Z_0 versus corresponding CRC measured on plots PB and PA. For CRC higher than 2%, the variation of Z_0 with CRC is limited and progressive. For CRC lower than 2%, Z_0 declines rapidly by more than one order of magnitude to reach $\sim 10^{-4} \text{ m}$. Such values are typical of soil surface very easily erodible by the wind. For the Sahelian field surface, a threshold of about 2% in CRC appears as critical to limit wind erosion and thus significant soil losses by wind erosion. This limit of 2% in CRC corresponds approximately to 100 kg ha^{-1} of crop residues. Maintaining a CRC higher than 2% before the beginning of August, when wind erosion decrease (see below), would require a CRC of at least 12%, or approximately 800 kg ha^{-1} of crop residues after land clearing if performed in January ([Fig. 7](#)).

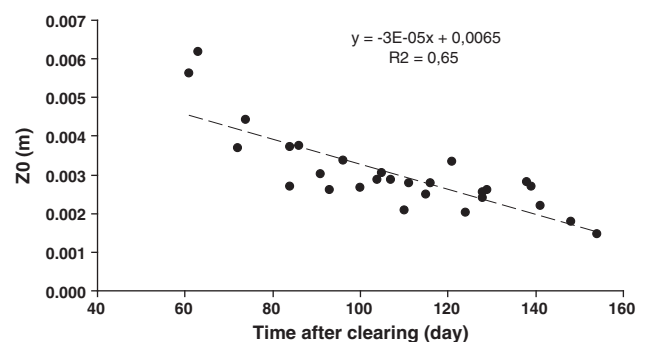


Fig. 10. Evolution of Z_0 as a function of time after clearing on plot PB for winds direction parallel to the longest plot axis ($232^\circ \pm 6^\circ$) in 2006 and 2007.

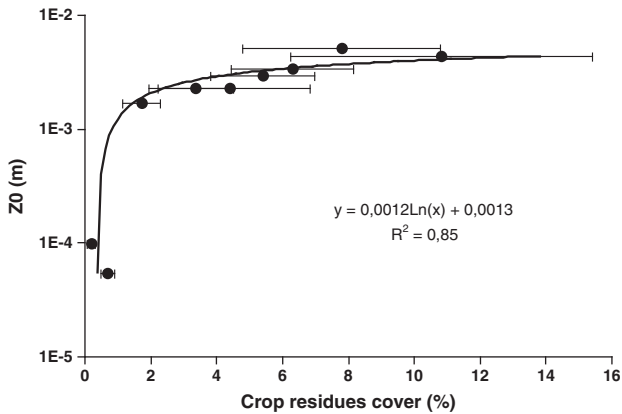


Fig. 11. Relation between aerodynamic roughness length (Z_0) and the Crop Residue Cover (CRC).

3.2.2.3. *The influence of Z_0 on erosion threshold speed.* The threshold speed derived from the saltiphones measurements can be compared between the two plots. A higher Z_0 , implies a higher threshold (Marticorena and Bergametti, 1995; Marticorena et al., 1997), i.e. a higher wind energy in order to set soil particles in movement. Accordingly, the average threshold speeds at 2.5 m above the surface are respectively 5.8 m s^{-1} ($\pm 0.3 \text{ m s}^{-1}$) and 7.3 m s^{-1} ($\pm 0.2 \text{ m s}^{-1}$) on plots PA and PB (Fig. 12). It was not possible to detect a significant temporal change in erosion threshold speed on plot PA since the bare surface did not change much with time. Although CRC, hence Z_0 decreased on plot PB, it was also not possible to measure a significant temporal change in erosion threshold speed on plot PB.

During the year, the daily averaged wind speed stayed below the threshold speed of each of the two plots (Fig. 4). This shows that the daily averaged speed has little significance for wind erosion studies. On the other hand, the daily maximum wind speed often exceeded the thresholds (Fig. 4). Both PA and PB threshold speeds were largely exceeded by the very high wind speeds in the front of the squall lines at the beginning of the rainy season, but during the Harmattan period only PA threshold was regularly exceeded.

Based on Eq. (4) and on the measured roughness height Z_0 , the threshold speeds of erosion were converted in wind friction threshold velocity (U^*t), which is more generally used in wind erosion models (Marticorena and Bergametti, 1995; Visser et al., 2005b). A relatively constant U^*t of 22 cm s^{-1} was obtained for plot PA. On plot PB, U^*t decreased from 46 cm s^{-1} to 36 cm s^{-1} due to the decrease in the Z_0 observed between April and July (Figs. 9 and 10). Sow et al. (2009) measured U^*t ranging from 30 to 40 cm s^{-1} on a millet field, located only 300 m from the plots used in this study, and cultivated as plot PB.

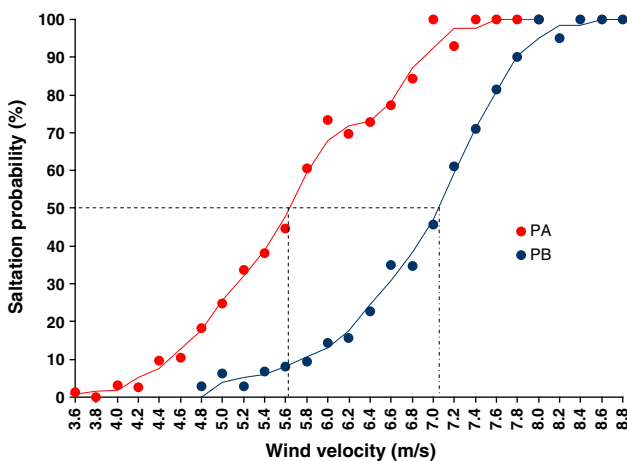


Fig. 12. Wind erosion threshold on PA and PB in April 2006.

These results suggest that the method of estimating the threshold speed of erosion used in this study provides a reasonable assessment of the theoretical erosion thresholds.

For the Z_0 measured in this study, the drag partition scheme developed by Marticorena and Bergametti (1995) to estimate the erosion wind friction velocity gives much higher U^*t than the one obtained here. The difference can be explained by the fact that this scheme has been established and validated using wind tunnel-measurements of U^*t and Z_0 for artificial roughness elements or surfaces covered by stones or field measurements over vegetated surfaces with small perennial bushes (Marticorena and Bergametti, 1995; Marticorena et al., 1997). The overestimation of the erosion threshold by this scheme over natural vegetated surfaces was already noted by MacKinnon et al. (2004). In our case, crop residues are not always flattened to the soil, but exhibit spaces between the straws and the soil able to create turbulence or intense local accelerations in air flow that produce erosion (Sterk and Spaan, 1997).

3.2.2.4. *The horizontal flux of saltation.* Saltation flux measurements on traditionally cultivated plot PB and bare plot PA are presented in Fig. 13. For each plot, the average flux has been computed as the average of all the BSNE measurements over the plot. The flux is then cumulated over the four consecutive years. The shape of the curve obtained for plot PB is very typical of the wind erosion flux dynamic, as already monitored in the Sahel (Rajot, 2001; Biielders et al., 2004; Tidjani, 2008; Rajot et al., 2009). It shows an intense erosion period from May to mid-July, which corresponds to the beginning of the rainy season (Michels et al., 1995b; Buerkert et al., 1996). This Aeolian erosion period can be explained by the occurrence of extremely intense winds (Fig. 4) associated with convective systems passing over a surface where crop residues cover is at its minimum (Biielders et al., 2004; Sow et al., 2009). Ninety percent of the eroded mass fluxes were recorded during this period for PB, with an average flux of $3.9 \text{ kg m}^{-1} \text{ d}^{-1}$ over the three-year period of measurement. This Aeolian erosion phase was much more intense on plot PA, with an average flux of $12.2 \text{ kg m}^{-1} \text{ d}^{-1}$. The erosion flux is about three times higher than on plot PB.

Surprisingly, this erosion phase dramatically decreased on both PA and PB at the same period. This decrease of wind erosion in the Sahel around mid-July was previously supposed to be due to the progressive increase in surface roughness, and thus in erosion threshold, induced by the development of vegetation (e.g. Biielders et al., 2004). But, as plot PA was maintained bare, the decrease in erosion flux can only be due to changes in meteorological conditions and in particular in surface wind speeds. Fig. 14 show the erosion events duration, the maximum wind speed, and the time between 2 successive rainfalls for the year 2007. The number of wind erosion events dramatically

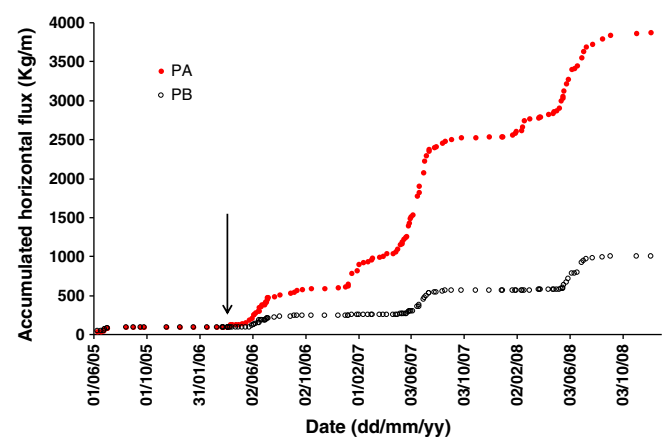


Fig. 13. Accumulated average horizontal fluxes on PA and PB monitored from June 2005 to December 2008 (the arrow indicated the beginning of PA stripping treatment).

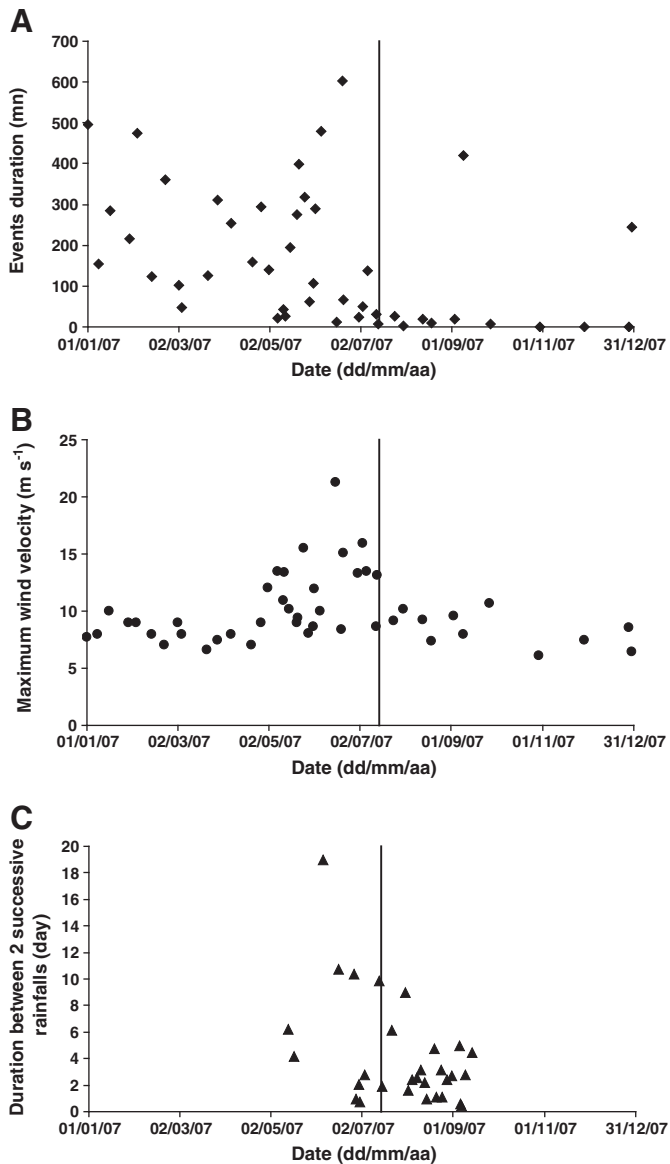


Fig. 14. Characteristics of wind erosion events during the 2007 year. A: Events duration, B: maximum wind speed during events (averaged over 5 min) and C: duration between two successive rainfall events.

decreased after mid-July: 11 erosion events were records between the 1st of June and the 15th of July but only 4 between the 15th of July and the 1st of September. The event duration and the wind intensity are also significantly lower after the 15th of July. On the opposite, no change in the frequency of rainfall is observed around mid-July. As a result, the observed change in wind erosion cannot be due to a higher top soil humidity that would inhibit the erosion by an increase of the wind erosion threshold (Fécan et al., 1999).

On plot PA, wind erosion at the beginning of the rainy season represents only 66% of annual erosion fluxes. Erosion fluxes are recorded even during the dry Harmattan season, from January to April. Dry season's erosion fluxes represent ~25% of the annual fluxes on PA, i.e. an average flux ($3.7 \text{ kg m}^{-1} \text{ d}^{-1}$) comparable to the flux measured during the major erosion phase in the rainy season on PB ($3.9 \text{ kg m}^{-1} \text{ d}^{-1}$). This erosion phase on PA is clearly due to the very low Z0 and thus an erosion threshold speed often lower than the maximum winds of the same period (Fig. 12).

Such local erosion events in Harmattan conditions have already been identified by Rajot et al. (2008) in natural conditions. At this period, surface wind speed in the Sahel exhibits a typical diurnal cycle

of wind characterized by a short duration maximum around 12 h during which wind erosion is sometime detectable. However, intensity of erosion appears to be very low in the present environmental conditions. Indeed, the contribution of local erosion to the atmospheric suspended desert dust concentration was estimated to ~1.5% during the one month period of measurements, from January to February 2006 (Rajot et al., 2008). This is explained by the fact that dry season erosion events do not significantly affect cultivated surfaces, and mainly concerns bare surfaces, such as areas around villages or ponds where livestock drink.

Finally, over the total period of monitoring after the stripping of PA (between April 2006 and December 2008), the cumulated erosion flux is about 3800 kg m^{-1} on PA and four times lower on PB ($\sim 900 \text{ kg m}^{-1}$).

The effect of crop residues has been documented for USA's Great Plains to establish the RWEQ (Revised Wind Erosion Equation) an empirical wind erosion model (Fryrear et al., 1998). This model was validated by Horning et al. (1998) in another region of USA, the Columbia Plateau, based on portable wind tunnel experiments. The erosion fluxes from our study can be compared to the results obtained with the equation describing the decrease of horizontal flux with soil residue cover and random roughness proposed by Horning et al. (1998). In our case, there are neither clods nor stones at the soil surface and we assume a random roughness of 0.5 cm. Horning et al. (1998) estimated the ratio between the erosion flux on a treated plot and on a bare plot to range between 0.70 and 0.42 for soil cover ranging respectively from 2 to 12%. In our case, the ratio of erosion fluxes on plot PB and PA is much lower, since it did not reach 0.25 during the whole experiment duration. This difference could be due to a higher roughness produced by millet straws which are larger than the wheat used to establish the equation. In addition, the wind velocities used in the wind tunnel studies ($12, 15$ and 18 m s^{-1}) are much higher than those actually recorded close to the surface during natural erosion in the Sahel. These differences outline the difficulty to generalize measurements obtained in different regions of the world, with different agricultural practices and with different experimental methods.

Our results are closer to the one obtained by Lancaster and Baas (1998) under natural wind erosion conditions. These authors measured saltation fluxes 3 times higher on a bare sandy soil than on a surface with natural vegetation cover of about 4%. Nevertheless, it is difficult to compare such results with ours because 1) their plots were not isolated from incoming fluxes from neighboring surface with different cover and mainly because 2) vegetation cover is not due to litter of crop residues but to standing natural grass. Even if the natural straw diameter is similar to wheat, the fact that natural grass was erected during the measurements could explain that the decrease of erosion fluxes are of the same order of magnitude than those we measured with flat crop residue. This suggests that pastured grass land could have the same behavior than cultivated fields regarding the effect of vegetation cover on wind erosion.

3.2.2.5. Inter-annual dynamics. During the four years of measurement, a different evolution in wind erosion fluxes was recorded on the two plots. On plot PB, the cumulated fluxes recorded at the beginning of each rainy season erosion period steadily increased from 2006 to 2008 (Table 1). This evolution may be explained by an increase in the wind speeds from 2006 to 2008. However, plot PA did not follow the same evolution. This suggests an increase in the erodibility of the soil rather than in the erosivity of climate. A similar increase in erosion flux intensity with the duration of cultivation was previously observed by Biielders et al. (2001). These authors explained this increase by a decrease in CRC which could be due to the weak trend of yield decline over years of successive cropping as observed by Hiernaux et al. (2009). No significant inter-annual evolution in CRC was measured during our experiment, but the CRC values tend to be very close to the

Table 1

Comparison of horizontal flux (Fh) measured on PA (after stripping treatment) and PB. For each year of the experiment, fluxes are accumulated over the beginning of the rainy season and accumulated over the second part of the dry season.

Year	Accumulated Fh (kg m ⁻¹) for the second part of the dry season 1st of January to 30th of April		Accumulated Fh (kg m ⁻¹) for the beginning of the rainy season 1st of May to 15th of July	
	PA	PB	PA	PB
2006	nd	nd	339.7	117.7
2007	455.8	2.8	1318.4	281.2
2008	319.5	5.7	824.8	394.2

nd = no data, stripping treatment of PA was not performed.

2% threshold during the erosion period and small undetectable variations may have great influence on flux intensities (Fig. 11).

In contrast, a very strong increase in accumulated flux was observed on plot PA during the second year of treatment, followed by a decline in the third year. An equal decline was observed during both the dry and the rainy season (Table 1). This evolution can be explained by the development of erosion crusts (Casenave and Valentin, 1992) on the soil surface, which led to a supply limitation of the particles available for saltation. In the same area, Rajot et al. (2003) did not observe any effect of soil crusting on wind erosion fluxes. However, they studied sieving crust (Casenave and Valentin, 1992) which considerably differ from the erosion crust observed in the current study, which is almost exempt from free sand particles on its surface, as described in other studies where supply limitation was well observed (e.g. Gomes et al., 2003).

4. Conclusions

Sahelian soils generally formed on aeolian sand deposits and are thus particularly susceptible to wind erosion once natural vegetation is cut down for cultivation. Our results suggest that very low crop residues density (around 100 kg ha⁻¹), essentially in the form of millet stalks, can be sufficient to reduce the potential wind erosion by at least a factor of 4. This reduction is due to the increase in aerodynamic roughness, which controls the threshold speed of Aeolian erosion. In traditional farmer fields under 500 mm rainfall, the threshold speed is almost never reached in the dry season and significant erosion events rarely occurs before the arrival of intense winds associated with convective systems at the beginning of the rainy season. Conversely, below a CRC threshold of 2%, surface winds are strong enough during the dry Harmattan season to provoke wind erosion. Such dry season's wind erosion events may have more negative effects on soil fertility than erosion at the beginning of the rainy season. Indeed, in the wet season, rains associated with convective systems can scavenge fine eroded dust that and thus prevent it from long-range transport. On the opposite, dust emitted during the dry season can travel over long distances, potentially leading to a general decrease in fertility in the study zone.

Our results show that a crop residues density of about 800 kg ha⁻¹ is necessary just after field clearing to reach a CRC slightly above the threshold of 2% five months later, during the most intense wind erosion period. Thus a simple way of reducing wind erosion could be to maintain, as long as possible, crop residues standing in fields and to clear fields just before sowing pearl millet. The efficiency and feasibility of this solution still requires further study. Indeed, wind erosion is not the only factor that controls millet field yield. Soil organic matter is also an important factor and an early clearing of fields may allow a better incorporation of organic material into soils during the dry season.

The density of 800 kg ha⁻¹ corresponds to that currently available in the study area for a mean rainy season of about 500 mm. Due to the

decreasing gradient of precipitation typical of the Sahel the CRD is expected to be lower in the North Sahel, where millet is still cropped on sandy soil under rainfall depth of only 300 mm per year. This suggests that wind erosion is an increasing threat for millet field toward the north of the Sahel. In the East of Niger near Maradi, farmers collect millet straws for cattle feeding just after harvesting. Consequently millet field remains almost bare in dry season and wind erosion events can be observed in this area during dry season. Such a practice is thus expected to decrease soil fertility and thus not sustainable on the long term.

In addition to the impact of agricultural practices on wind erosion, this study also presents evidence that the decrease in wind erosion during the wet season is controlled by a major meteorological change occurring around mid-July, after which wind erosion does not usually occur in the Central Sahel.

Finally, the development of erosion crusts linked to wind erosion when the CRC is too low to inhibit wind erosion is an important phenomenon that leads without doubt to a decrease in erosion fluxes, but which also favors runoff (Casenave and Valentin, 1992) and water erosion. This phenomenon, observed on the experimental plots, can be found on a much larger scale in the Sahelian landscape (Abdourhamane Touré et al., 2011). Thus, even if the impacts of climate change are a major concern for the Sahel, this work confirms that the impact of human activities is currently of first importance for the Sahelian Environment.

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