Wind and water erosion of non cultivated sandy soils in the Sahel: a case study in Northern Burkina Faso, Africa

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Abstract

In the Sahel, sandy soils are widespread and support not only most of pearl millet production, the major staple crop in the region, but also forage production for livestock. Parent sediments of these soils have an aeolian origin and hence are prone to wind erosion. However, the clay content, albeit very low, results in the formation of crusts during rainfall, thus leading to runoff and water erosion. Squall lines, major rainfall events of the rainy season, are usually preceded by intense wind. Wind and water erosion is thus closely associated both in time and in space, but they are rarely studied simultaneously. Erosion measurements were carried out during two years (2001, 2002) on a small catchment of grazing land (1.4 ha) at Katchari, Burkina Faso, typical of the Sahel area under 500 mm annual rainfall. Wind erosion occurred at the onset of the rainy season, when soil cover is the lowest, from May to 15th of July, before vegetation growth. Water erosion occurred throughout the rainy season, but some intense events produced most of the total annual erosion.

Wind caused the largest sediment fluxes leading to both erosion (up to 20 Mg ha^{-1} yr^{-1}) and deposits (up to 30 Mg ha^{-1} yr^{-1}) according to the area of the catchment. Water erosion is one order of magnitude lower than wind erosion, and is more intense where wind erosion is the highest. Thus the same area is eroded both by wind and water. Conversely, in areas where there are aeolian deposits, water erosion is low and these areas correspond to fertile islands where vegetation grows. At this study scale, there is no land degradation, but intense dynamics leading to a high spatial variability typical of the Sahelian environment. On this uncultivated area, the dynamics were similar to those recorded in other Sahelian cultivated millet fields.

1. Introduction

In the Sahel, sandy soils are dominant. In Niger, for example, they represent more than 80% of the agro-pastoral zone (Gavaud, 1977). They support most of the annual vegetation growth, pearl millet, the main staple crop, and forage for livestock. Consequently, they play a major role for the farmers who represent more than 80% of the Sahelian population (Thiombiano, 2000; Guengant and Banoin, 2003). On these soils, both wind and water erosion occurs, but these two forms of erosion are rarely studied simultaneously. Wind erosion data, scarcer than than that on water erosion, can be found in the literature for cultivated areas (fields and fallows). At the field scale, soil loss due to wind erosion is found to reach very high levels (more than 25 Mg ha^{-1} yr^{-1}, Bielders et al. 2001). However, very few studies concern uncultivated areas where grazing is the only land use. Soil losses by water erosion in the Sahel seem to be lower (Collinet and Valentin, 1985), but, as measurements were not carried out on the same surface (same surface features and same surface area), they are difficult to compare. However a recent study (Visser, 2004) addressed estimation and comparison of wind and water erosions based on field work and modeling in the same area as the present work. Her results confirm those of previous studies, i.e. sediment and nutrient fluxes associated with wind are generally several orders of magnitude larger than those due to runoff. Her data were obtained at the erosion event scale on plots installed on two cultivated fields and one degraded surface with bare gravelly soil, but no measurement was performed in the grazing area. The objective of our work was to quantify wind and water erosion simultaneously in small grazing catchments with different surface features, over 2 seasonal cycles (2001 and 2002).

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2. Materials and methods

2.1 Study area

The study area is located in the North of Burkina Faso (UTM30, WGS84, 809847 m East, 155093 m North), near Dori, 250 km Northeast of Ouagadougou (Figure 1). The climate is of the Sahelian type, with a long dry season and a short rainy season from May to September. Average annual rainfall recorded in Dori from 1925 to 1998 was 512 mm. The grazed areas of the village lands are located on a low longitudinal slope (about 1%). They show two main soil types: i) large areas of bare crusted clayey soil patched with ii) areas of sandy soil that have developed on aeolian sand deposits (microdunes less than 0.7 m thick) where annual vegetation, shrubs and trees grow (Ribolzi *et al*., 2000). Within this zone a small representative catchment (1.4 ha) was selected composed of five main soil surface types according to the classification of Casenave and Valentin (1992) (Figure 1): (1) bare erosion surfaces (ERO) accounted for 33.6% of the total catchment area, (2) pavement surfaces (G), which were also bare, covered 0.4% of the catchment area, (3) sedimentation surfaces (SED) covering the bottom of ponds and depressions, accounted for 1.2% of the catchment area, (4) runoff type surfaces (RUN) consisting mainly of laminated materials of various textures, represented 4.2% of the catchment area, and (5) the drying surfaces (DRY) which covered the leeward area of sandy microdunes represented 59.9% of the catchment area. Microdune soils accounted for 69% of the total catchment area and constituted almost exclusively the support for annual vegetation, shrubs and trees. The windward sides of microdunes accounted for 14.3% of the total catchment area; they were characterized by a steep fragmented ERO surface (i.e. crumbling of the laminated structure of plasmic and sandy layers called ERO/S) resulting from wind deflation. These observations served ground to the selection of three sub-areas homogeneous in terms of surface feature combinations (Figure 1).

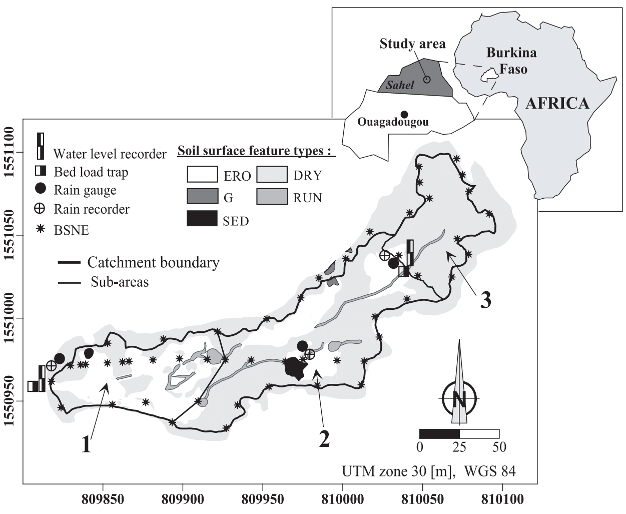

Figure 1. The study area, map of soil surface features, experimental design and boundaries of the 2 catchments for which water erosion was calculated and of the 3 sub-areas for which wind budget was calculated

Measurements of both wind and water erosion were undertaken from the 1st of June 2001 to the end of September 2002.

2.2 Water erosion measurements

In this study, it was not possible to use classical water erosion plots because artificial boundaries act as windbreaks, causing significant aeolian sand deposits. To avoid such disturbances, water erosion was measured on two natural nested catchments. The upstream catchment (0.3 ha) corresponds to sub-area 3 on Figure 1.

Rainfall was monitored using three simple rain gauges and three rainfall recorders. The stream discharge of each catchment was measured using flow recorders. Suspended matter fluxes at the outlets were estimated from discrete 1-litre water samples collected throughout runoff events with a time interval varying from 2 to 5 minutes. Bedload was collected in sediment traps after each event. The totality of these materials was dried and then weighed.

2.3 Wind erosion measurements

Unlike cultivated land where field/fallow transitions have to be taken into account in wind erosion studies (Bielders *et al*., 2002), in Sahelian grazing land there is no clear boundary acting on wind erosion. Thus, the limits of the areas under study are determined by those of water erosion (main catchment and upstream catchment [sub-area 3] boundaries) and by surface feature patterns (sub-areas 1 and 2) (Figure 1).

Wind-blown sediment fluxes were obtained using 50 masts equipped with 3 BSNE sand catchers (Fryrear, 1986) of 0.05, 0.15 and 0.3 m in height. The masts were placed 1) on the sub-area boundaries approximately every 20-m and 2) along a transect in the western side of the catchment (Figure 1).

Wind-blown sediments caught in BSNE were collected if possible after each erosion event from June to September and each month from October 2001 to May 2002. The horizontal fluxes were calculated at each mast by integrating the sediment flux density profile between 0 and 0.4 m height. Wind speed and direction were measured using an automatic weather station. An acoustic saltation sensor (Saltiphone, Span and Van den Abeele, 1991) indicated the period during which the fluxes were significant. With this information, it was possible to estimate the mean direction of wind during each storm event, and to determine the upwind and downwind limits of catchments; the incoming and outgoing mass fluxes along the boundaries of the catchments were then calculated by linear interpolation of sediment mass fluxes measured at each mast. The mass budgets within the sub-areas 1, 2 and 3 were calculated by subtracting outgoing from incoming wind-blown sediments.

Along the E-W transect, the BSNE masts were setup at each major surface feature change. When erosive wind direction corresponded to the transect direction (95 ± 15º), which was assumed to correspond to the more intense wind erosion events, it was possible to compute a budget by subtracting downwind from upwind fluxes and dividing the result by the distance between the two measurement locations.

Measurements of wind-blown sediments along the E-W transect were taken during the rainy season 2001.

3. Results and discussion

3.1 Dynamics of wind-blown sediment flux

Sand catchers were collected 57 times during the measurement period. Some data correspond to mixed events occurring at close intervals, or during the monthly period of collection. From meteorological measurements, it is possible to estimate that sixty-eight wind erosion events occurred during the 16 months of measurement. For the common period of measurement (June to September), there were 33 and 21 events in 2001 and 2002, respectively. The flux density at a height of 30 cm, averaged for the 50 BSNE masts (called FD_{30} below), accumulated over 2001 and 2002 was 25 and 22 g cm^{-2} , respectively. The inter-annual variability was lower than that measured in Niger from 1996 to 1998 (Rajot, 2001).

Only three events occurred during the dry season from October to March. These latter events represented less than 0.3% of the cumulative FD_{30} for the whole period. The first event of 2002 occurred on the 6th of April and was linked to the first rainfall of the year. As in a cultivated field in Niger (Rajot, 2001), the Harmattan wind did not produce wind erosion in this grazing area of the Sahel.

For the whole period, eight events produced 53% of the cumulative FD_{30}. Five of them occurred in June, two in July, and one in April. A few events at the onset of the rainy seasons produced most of the wind erosion.

Figure 2 shows the cumulative FD_{30} according to wind direction classes. 75% of the flux corresponded to wind blowing from the East to the Southeast (between 75º and 165º). This result corresponds closely with the local morphology of the microdune showing a higher slope on the windward side.

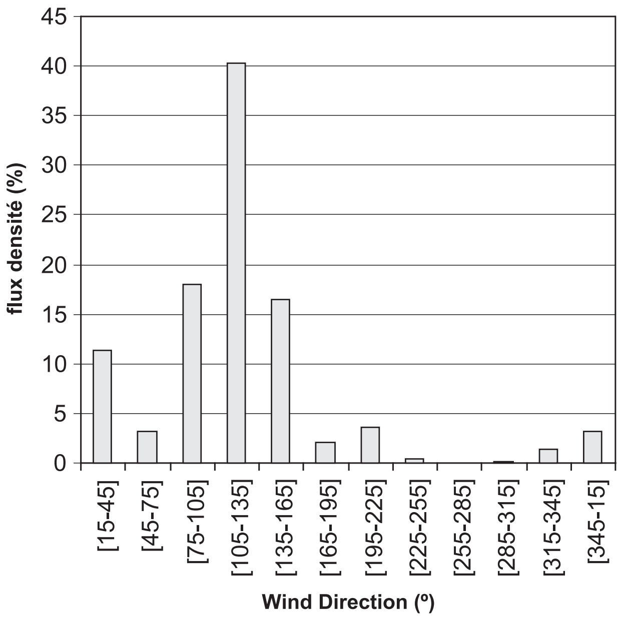

Figure 2. Percentage of flux density at 30 cm height averaged on the 50 BSNE masts and accumulated over the measurement period versus wind direction of events

All these observations correspond closely to other measurements suggesting a similar wind dynamic throughout the Sahel (Bielders *et al.*, 2004).

3.2 Wind-blown sediment budget within sub-areas

From the 68 events producing wind-blown sediment flux during the study period, it was only possible to calculate the mass sediment budget for a subset of forty-two events owing to mixed events or important variations in the wind direction for the other twenty-six. The cumulative FD_{30} for these forty-two computed events represented 87% of the total FD_{30} blowing out on the catchments during the entire measurement period. There was no major event, i.e.

with high sediment transport, among those events that were not considered. Thus, it will be assumed that the results obtained with these 42 events provide a good image of wind erosion on the catchments.

A Monte Carlo procedure was used for one major erosive event to estimate the standard deviation on budget result taking into account all the uncertainties affecting the computation, namely: the height of catchers, the surface of the opening, the fit of the theoretical equation for the calculation of horizontal flux, the position of the catcher on the area under study and the wind direction. The variation coefficients obtained ranged from 20% to 150% according to the sub-area and the differences between the sub-area budgets always remained highly significant.

Figure 3 shows the cumulative mass balances of aeolian sediment over the period of measurement for the three sub-areas. These areas behaved very differently: the budget is almost systematically positive for the upstream sub-area (#3) whereas it is systematically negative for the downstream one (#1), amounting to about +65 $Mg.ha^{-1}$ and -35 $Mg.ha^{-1}$, respectively, over the measurement period. Both erosion and deposition occurred in the centre sub-area (#2), but the budget remained positive over the measurement period (+27 $Mg.ha^{-1}$). At the catchment scale, these different behaviours of the sub-areas led to an almost balanced budget until the beginning of June 2002 (+3 $Mg.ha^{-1}$), and a really positive budget at the end of the measurement period (+16 $Mg.ha^{-1}$).

A high level of wind-blown sediment deposits was also reported by Bielders et al. (2001) for fallow land in Niger which presented similar surface features as sub-area 3 (dry crust with annual and perennial vegetation). The deposits were ascribed to the high surface roughness of these areas. In Niger, the sources of wind-blown sediments were pearl millet fields (Bielders et al., 2001). In this study, net wind erosion occurred on complex natural areas where all the different surface features encountered in the catchment are represented (Figure 1). Thus the surface features from where wind-blown sediments originate are still unclear and need to be assessed.

3.3 Wind-blown sediment budget along the transect

The transect measurements taken across sub-areas 2 and 3 (Figure 1.) enabled a better description of the processes occurring in relation with soil surface features. Only five events required the wind direction to be computed from the transect, but two of them were the more intense events of the 2001 season. General trends appeared and can be summarized from the budget computed from the sum of these five events (Figure 4). First of all, the transect revealed the high spatial variability of wind erosion at the meter scale. There was no systematic behaviour on the 2 main surface features with regards to the budget: erosion may occur on the DRY surface and deposits may occur on the ERO surface. Nevertheless, the larger deposits occurred on the DRY surface whereas the more intense erosion occurred on the ERO surfaces covering windward slope of sandy microdune (ERO/S) or areas where such a surface was present (between 70 and 85 m), as well as on the RUN surface.

ERO/S surfaces are closely associated to DRY surfaces and develop on the same sandy soil. If one considers these 2 surfaces together (between 0 and 9 m and between 25 to 37 m) the sediment budget is

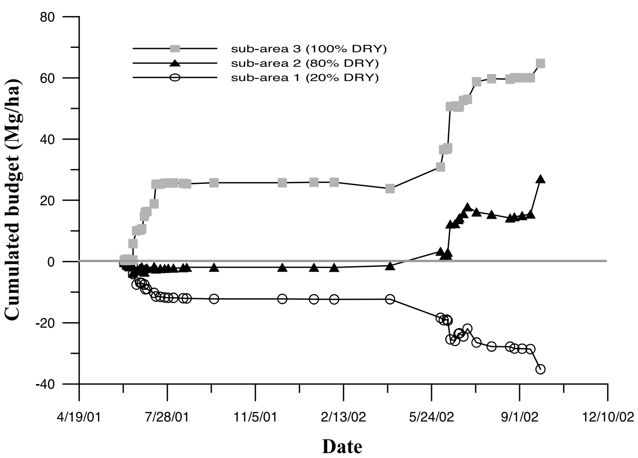

Figure 3. Wind-blown sediment mass budget ($Mg.ha^{-1}$) accumulated over the study period for the 3 sub-areas selected because of their surface feature distribution

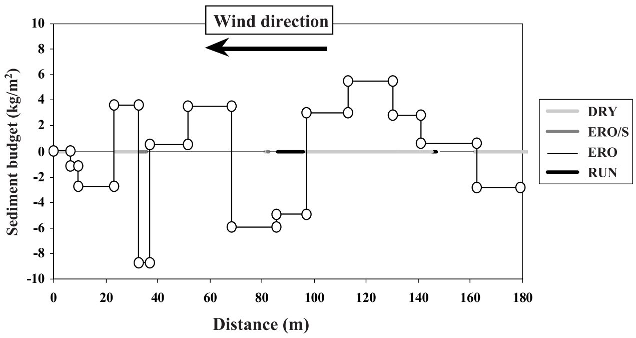

Figure 4. Accumulated wind-blown sediment budget for the five events with easterly winds (parallel to the transect orientation) versus distance from the western border of catchment. The various types of surface features (see text for description) are indicated by different shades of gray on horizontal axis

negative i.e. the small patches of sandy soil are currently subject to net erosion as suggested by Casenave and Valentin (1989) during drought conditions.

The fact that net deposits may occur on ERO surfaces whereas sand deposits were not observed suggests that these sediments are mobilized by water erosion which often follows wind erosion in the Sahel (Visser et al., 2004). Similarly, the high susceptibility of RUN surfaces to wind erosion shows that water erosion produces sediments that are easily mobilized by wind erosion.

3.4 Dynamics of water erosion

The annual rainfall levels were 325 mm in 2001 and 345 mm in 2002. Both years showed a deficit compared to the mean annual level (512 mm for the reference period of 1925-1998). Rainfall generated 16 floods in 2001 and 13 in 2002. The number of water erosion events was less than half the number of wind erosion events. Although the amount of rain was lower in 2001, more heavy events were observed during this year: rainfall levels exceeded 25 mm for only two events in 2002 compared to four events in 2001 (Figure 5). For the whole catchment, water erosion was twice as high in 2001 as in 2002, but it was the reverse for the upstream catchment (Figure 5). Water erosion, unlike wind erosion, occurred throughout the rainy seasons and did not show a period of clearly higher intensity. As for wind erosion, some events were responsible for a large part of the annual erosion. In 2001, the four most important rainfall events (level >25 mm) were responsible for 60% of water erosion

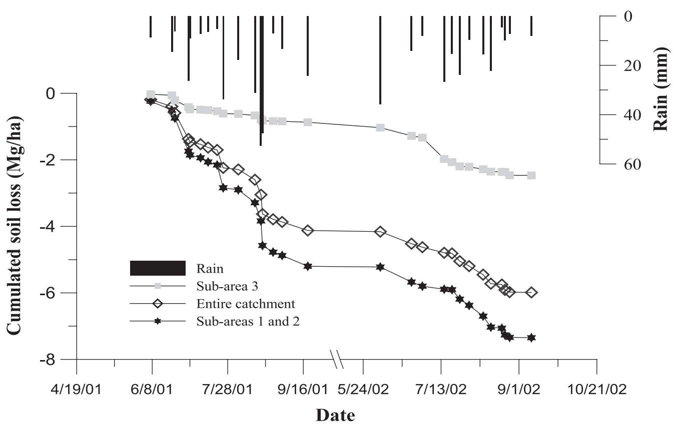

Figure 5. Rainfall depth and accumulated soil loss due to water erosion over the study period (rainy seasons 2001 and 2002) for the entire catchment, sub-area 3 (i.e. 100% DRY) and sub-areas 1 and 2 (between 20 and 80% DRY)

(Figure 5). Karambiri et al. (2003) already showed the similar behaviours in the same catchment for the period 1998-2000.

3.5 Water erosion within sub-areas

Cumulative soil losses by water for this period were estimated at 6.0, 2.5 and 7.3 Mg ha^{-1} yr^{-1} for the entire study area, the upstream zone (sub-area 3) and the downstream part of the catchment (sub-areas 1 and 2), respectively (Figure 5). Soil losses by water were lower upstream than downstream. These results conform closely to observations of Karambiri *et al*. (2003) in the same area (1998, 1999 and 2000 rainy seasons). They attributed the different behaviours of the two catchments to the soil surface characteristics: Drying surfaces, which are more permeable and supported herbaceous plants, covered the entire sub-area 3 and hence favoured infiltration rather than runoff. In contrast, the downstream zone was patched with impervious-prone erosion crust, which is more susceptible to erosion.

Particle size distribution of sediment exported varies according to the catchment. On the upstream sub-area, the exported sediments were composed mainly of sandy bedloads, while silty-clay suspended particles were dominant downstream (i.e. sub-areas 1 and 2). These results suggest that the clayey erosion crust could be a major source of sediment for water erosion; they correspond closely to the results reported by Karambiri *et al.* (2003) in the same study area.

3.6 Combined water and wind sediment budget

At the catchment scale, taking into account both wind and water erosion, and considering the whole study period, we estimated a positive cumulative budget of 10.2 Mg/ha. This result masks high spatial and interannual variabilities of the sediment budget (Table 1). There was a high positive budget on sub-area 3 due to wind sediment deposits (65 Mg/ha). Sandy sediments accumulated on sub-area 3 and were partially removed by water erosion (-2.5 Mg/ha) mainly in the form of bedload. Conversely, there was a negative budget on the downstream part of the catchment due to both wind (-0.4 Mg/ha) and water (-7.3 Mg/ha) erosion. For this sub-area, we observed a net wind erosion in 2001 (-6.4 Mg/ha), which was compensated by wind deposits in 2002 (6.0 Mg/ha). Such high spatial variability due to wind erosion in the Sahel was pointed out by Bielders et al. (2001) in a cultivated area. It also appears to be very high in grazing areas.

Table 1. Accumulated soil (Mg/ha) due to water and wind for the entire catchment, sub-area 3 and sub-areas 1 and 2

	water	wind	sum	water	wind	sum	water	wind	sum
	2001			2002			Cumulative totals		
Entire catchment	-4.1	1.1	-3.0	-1.9	15.1	13.2	-6.0	16.2	10.2
Sub-area 3	-0.9	25.7	24.8	-1.6	39.0	37.4	-2.5	64.7	62.2
Sub-areas 1 and 2	-5.2	-6.4	-11.6	-2.1	6.0	3.9	-7.3	-0.4	-7.7

In these areas, water erosion can locally reach the same order of magnitude as wind erosion and can move higher quantities of sediments (table 1). This result differs from that of Visser (2004) obtained for a cultivated field where wind erosion dominated.

4. Conclusions

For the first time in the Sahel, wind and water erosion was measured from the same surface areas of grazing lands, composed mainly of sandy soils. The main conclusions of this study can be summarized as follows:

1. Annual wind erosion dynamics for this grazing area are typical of the Sahel and are the same as observed for a cultivated field in Niger.
2. Wind erosion has a clearly oriented direction and is responsible for the asymmetric morphology of the microdune.
3. Wind erosion events are more numerous than those of water erosion and at the smallest scale are more intense, moving higher quantities of sediments.
4. There is a high spatial variability at the local scale with areas of net deposits, where vegetation grows and areas of net erosion where bare soils predominate.
5. Both wind and water erosion is more intense downstream and appears to be related to the type and size of surface features.

These results revealed the difficulties in estimating land degradation in the Sahel that depends heavily on the study scale. They suggest a strong linkage at the scale of a few meters between sediment source areas where degradation occurs and sediment sink area where vegetation develops in "islands of fertility". They emphasize the necessity of taking into account both wind and water erosion in order to assess the current land degradation in the Sahel.

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