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Wind blown sediment mass budget of Sahelian village land units in Niger

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Key words. – Sahel, Wind erosion, Aeolian deposition, Mass budget, Scale of village land units.

Abstract. – To assess the mass budget of aeolian sediments transported by wind (erosion *vs.* deposition) at the scale of village land units (25 km × 25 km), measurements were carried out during 3 years (from 1996 to 1998) in a cultivated field and in a fallow area simultaneously. These were located in the Sahelian zone of Niger with an average annual rainfall of 560 mm. The vertical upward fluxes of particles < 20 µm exported from the study area were estimated from the horizontal sediment fluxes measured using BSNE sand catchers. This mass of exported dust was compared with the vertical downward fluxes of particles of the same size range (< 20 µm) measured using passive CAPYR collectors.

Values of deposition recorded in the field and in the fallow were similar. In the field, wind erosion reached its maximum in May and June when the vegetation cover was minimal. In the fallow area, wind erosion was always very low in comparison with the field. It occurred during the strongest storms when the grass cover was minimal. Nevertheless, the net balance between deposition and erosion was highly positive in the fallow areas.

These results have been extrapolated at the scale of the village land units based on the current land use. At this scale, the balance was positive for the arable land, indicating a net deposition of aeolian sediments of + 0.36 t ha^{-1} yr^{-1}. However, the complete disappearance of fallow land would result in a balanced budget for the arable land.

Bilan de masse de l'érosion et des dépôts éoliens à l'échelle de terroirs villageois au Niger

Mots clés. – Sahel, Érosion éolienne, Dépôts éoliens, Bilan de masse, Échelle de terroirs villageois.

Résumé. – Pendant 3 ans, de 1996 à 1998, des mesures directes d'érosion et de dépôts éoliens ont été réalisées en continu et en parallèle sur un champ et sur une jachère au Niger sous un climat typiquement sahélien (560 mm de pluie annuelle). Le flux d'érosion vertical de particules < 20 µm exportées des sites étudiés a été calculé à partir du flux d'érosion horizontal mesuré à l'aide de capteurs de sable BSNE. Cette masse de poussières exportées a été comparée à la masse déposée, pour des particules de même taille (< 20 µm), quotidiennement mesurée à l'aide de capteurs passifs (CAPYR).

Les masses de sédiments déposées sur le champ et sur la jachère sont identiques. Dans le champ, l'érosion éolienne atteint son maximum en mai et juin lorsque le taux de recouvrement de la surface du sol par les résidus de culture est minimal. Dans la jachère, l'érosion éolienne est toujours négligeable par rapport au champ. Elle se produit pendant les tempêtes les plus violentes lorsque le taux de couverture par les herbacées est minimal. Néanmoins, le bilan net entre l'érosion et les dépôts éoliens est toujours très largement positif dans les jachères.

Ces données ont ensuite été spatialisées à partir d'hypothèses simples à l'échelle de terroirs villageois (25 km × 25 km). En l'état actuel de l'occupation des sols, le bilan est positif sur les sols arables ce qui correspond à un dépôt net de poussière de + 0,36 t ha^{-1} an^{-1}. Cependant, en supposant que la totalité des terres arables soit cultivée sans aucune jachère, le bilan deviendrait équilibré.

INTRODUCTION

Sandy soils of aeolian origin represent 80 % of the soils in the southern part of Niger [Gavaud, 1977]. These soils have low native fertility [Manu *et al.*, 1991] but are suitable for growing pearl millet (*Pennisetum glaucum* (L.) R.Br.), the major staple crop in the region. As commonly observed in the Sahel, the rapid population increase over the past few decades in the southeastern part of Niger has led to a land pressure increase. For example, on the East Central Supersite of Hapex-Sahel, 60 km east of Niamey, the cultivated area (field plus fallow) represented 17, 49 and 100 % of the arable land in 1950, 1975 and 1992, respectively [Loireau *et al.*, 2000]. Because of the major role of these soils in food production, it is paramount to study the impact of such increasing land pressure on water and wind erosion.

The first step is to quantify erosion, in terms of mass budget (gains *vs.* losses). When used without further specification, the word "erosion" usually refers to water erosion. However, many studies have shown that in the Sahel wind erosion is also responsible for substantial soil losses [see, e.g., Bielders *et al.*, 1998]. For these two erosion types, the values of losses or gains are closely linked to the scale of observation. Water erosion data has often been obtained

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from rainfall simulations on small plots (from 1 to 50 m^2). Collinet and Valentin [1985] estimated that soil losses from bare plots range from 80 t $ha^{-1}yr^{-1}$ in Ivory Coast (2,000 mm average rainfall) to 2 t ha^{-1} yr^{-1} in the northern part of Sahel (150 mm average rainfall). At the scale of a small watershed of 0.9 km^2 in the Sahelo-Sudanian area (mean annual rainfall of 649 mm yr^{-1}), Albergel *et al.* [2000] measured soil losses ranging from 0.38 to 3.5 t ha^{-1} yr^{-1} depending on the annual rainfall (on average 1.4 t ha^{-1} yr^{-1} during 4 years). Nevertheless in the selected region of Niger, the hydrological units are endoreic watersheds with an area less than 10 km^2 [Desconnets *et al.*, 1997]. Thus, due to the hydrologic nature of the watersheds, water erosion can be considered as nil at the scale of village land units (25 km × 25 km).

The available wind erosion budgets calculated from direct wind erosion measurements in the Sahelian region are scarce. The mass budget method requires the measurement of incoming and outgoing horizontal airborne sediment fluxes. Current estimates of wind erosion are based on plots with an area ranging from a few hundred to a few thousand square meters. Sterk and Stein [1997] have computed that over an experimental millet field (40 m × 60 m) at the ICRISAT Sahelian Center in Niger, only 4 storms caused a net soil loss of 45 t ha^{-1}. According to Bielders *et al.* [2000] the potential net soil loss averaged over three years was in excess of 119 t ha^{-1} for bare cultivated plots (15 m × 20 m) located in a farmer's field in western Niger. In the same field but with a millet straw mulch of 2 t ha^{-1}, these authors estimated potential net deposition to be in excess of 111 t ha^{-1} over three years. These examples highlight the high variability of data collected at the plot scale. Up to now, no data is available based on direct wind erosion measurements either at the scale of the whole cultivated field or at the village land units scale. A few authors studied dust deposition in the Sahelian zone of Niger [Drees *et al.*, 1993 ; Herrmann, 1996] indicating annual deposition rates ranging from 0.8 to 2 t ha^{-1} yr^{-1}. These studies have been conducted in areas protected from wind erosion and therefore cannot be generalized at larger scales, particularly those which include cultivated fields subject to wind erosion [Herrmann *et al.*, 1996].

The aim of this work is to estimate a wind-blown sediment mass budget at the scale of village land units (25 km × 25 km) representative of the Sahelian zone in southwestern Niger. For this purpose, measurements were made over a 3-year period of sediment fluxes in a traditionally cultivated field and a fallow field. The results were then extrapolated to provide an estimate of wind erosion at the village land units scale.

MATERIALS AND METHODS

Experimental sites

Wind erosion budget was computed over a 3-year period (1996-1998) for an area 25 × 25 km^2 surrounding the village of Banizoumbou, 60 km east of Niamey, in southwest Niger (fig. 1). The climate is typically Sahelian with a long dry season and a short rainy season from June to September (564 mm annual average rainfall in Niamey, Lebel *et al.* [1997]). Annual rainfall was 510 mm, 425 mm and 662 mm in 1996, 1997 and 1998, respectively. This region has two

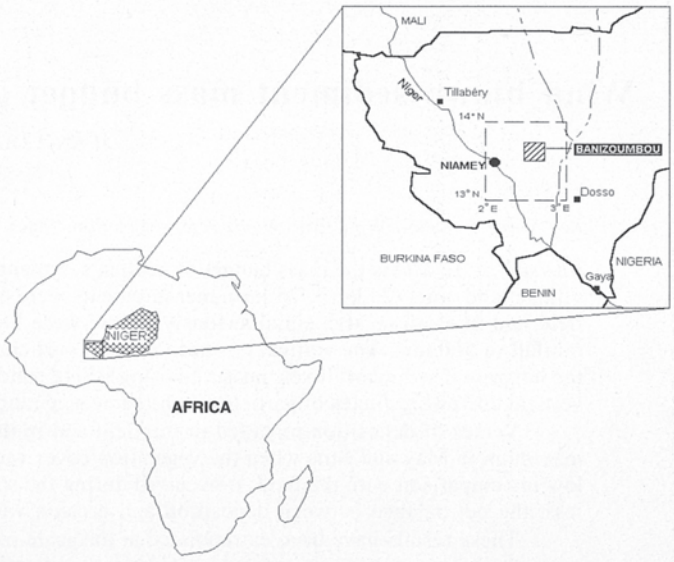

FIG. 1. – Location of village land unit of Banizoumbou in southwest Niger, West Africa.
FIG. 1. – *Localisation du terroir de Banizoumbou au sud ouest du Niger (Afrique de l'Ouest).*

main geomorphologic units [d'Herbès and Valentin, 1997]: non cultivated lateritic plateaus with banded vegetation – referred to as tiger bush [e.g., Ambouta, 1997] – and sandy arable land in the valleys with different sub units [Chappell *et al.*, 1998]. On the plateaus, the topsoil clay content is high (25%), the bare soils are crusted and the tiger bush is often organized in large concentric circles [Ambouta, 1984]. Both these factors provide very efficient protection against wind erosion [Gillette, 1999] which will be assumed to be nil hereafter for the lateritic plateaus.

Wind erosion and deposition were monitored during 3 years in a millet field and an adjacent fallow (13°31'30"N, 2°38'21"E). These sites were located on a sandy substrate covering several kilometers from west to east, from the « Erg Ancien », i.e. > 40,000 B.P. [Boulet, 1978]. The soils of both sites were classified as « Sols ferrugineux tropicaux peu lessivés » [CPCS, 1967], or sandy psammentic Haplustalf [Soil Survey Staff, 1975]. On average, the topsoil (0-5 cm) had a low content of fine particles (2.8 % clay, 2.4 % silt) and in organic carbon (0.2 %).

The experimental sites were located 2 km from the village, in an area cultivated in a traditional way with fallow periods alternating with cropping periods without manure [de Rouw, 2000]. The studied field (25 ha) had been cultivated with pearl millet (*Pennisetum glaucum* (L.) R.Br.) since 1992 after an 8-year fallow period. The adjacent fallow site (20 ha) had been left fallow since 1991 after a 5-year cropping period.

Method for calculating wind erosion budget

Wind erosion is usually characterized by a horizontal flux Fh and a vertical flux Fv [Gillette, 1979]. The horizontal flux corresponds to the mass of sediment transported per unit area perpendicular to the wind and integrated over the height of the saltation layer. It is expressed in kg m^{-1} per unit time. It corresponds to particles < 500 µm in diameter moving by saltation over the soil surface. This flux reaches

[Gillette, 1977]. The horizontal saltation flux (Fh) was measured in Niger by the means of 4 masts each of which being equipped with 3 BSNE (Big Spring Number Eight ; Fryrear [1986]) sand catchers at height of 10, 22.5 and 35 cm. They were placed at 30 meters north, east, south and west from the meteorological masts, in the center of the field and the fallow and were kept in place all year round.

The horizontal sediment fluxes over eroding area increase from boundary of the area until they reach a maximum [Fryrear and Saleh, 1996]. It was verified [Valentin *et al.* 2001] that the measured horizontal fluxes corresponded to the stabilized ones i.e. to the maximum fluxes of sediment in the field and to the minimum in the fallow. The use of these values in the computation of budget probably leads to an overestimation of erosion because the stabilization of fluxes is faster in the fallow than in the field [Bielders *et al.*, 2001] and because the maximum fluxes may not be reached in the smallest fields.

The sediment caught in the BSNE catchers were collected and weighted after each erosion event. If it had rained after the wind erosion event, the sediment was oven dried at 105°C for two days before being weighted. The horizontal flux profile was then obtained by fitting the measurements at the 3 given heights to the theoretical equation [Fryrear and Saleh, 1993]:

$$Q(z) = a.e^{-b.z} \quad (1)$$

z being the height above ground of the center of the BSNE opening (cm),

Q(z) the horizontal flux at height z, in $g.cm^{-1}$,

a and b are constants which have respectively dimensions of mass flux ($g\ cm^{-1}$) and cm^{-1}.

Equation (1) was then integrated for each mast up to 40 cm height and Fh ($g\ cm^{-1}$) was the average of the 4 measurement locations within each land use type.

RESULTS AND DISCUSSION

Deposition

Deposition fluxes measured in the field and in the fallow were closely positively correlated (fig. 2a) except when rainfall occurred (fig. 2b). In this case, the correlation was weak and no clear tendencies appeared. In 1996 and 1998, the deposits on the fallow were slightly higher than on the field. The reverse was observed in 1997 giving a perfectly balanced total for the whole 3 years (299 $g.m^{-2}$ in the field and 298 $g.m^{-2}$ in the fallow). This result led to consider hereafter that the deposition flux was homogeneous at the scale of the village land units. It will be represented by the fallow CAPYR measurements because it was placed in the same vegetation unit as the collectors of Herrmann [1996] used for the particle size corrections.

The seasonal dependence of the total deposition flux was plotted in figure 3. The same trends could be observed each year with differences in frequency and intensity of events. Broad peaks with increasing intensities were observed during the Harmattan season (October through March). They were associated with dry haze events that lasted generally several days. Background measurements also increased during that period, which indicated a permanent and relatively high dust load in atmosphere. In May, June and July (beginning of the rainy season) numerous intense narrow peaks were observed. These deposition events were associated with local erosion events such as dust storms occurring just before mesoscale convective systems. The background load decreased because rains washed dust out of the atmosphere. By the end of the rainy season (August to October), the peaks due to passing storms had low intensity because vegetation cover prevented intense local erosion. A very low background level was associated with a clear atmosphere. Between the 8th and the 10th of October 1997 an intense event occurred (fig. 3). It corresponded to an exceptional wind erosion event in the vicinity of Gao (Mali). April is a transition period between the Harmattan and the beginning of the rainy season with both dust hazes and local erosion events.

Without particle size correction, the overall sediment deposition flux including particles > 20 µm amounted to 0.73, 0.97 and 1.28 $t\ ha^{-1}\ yr^{-1}$ for 1996, 1997 and 1998, respectively. These values were consistent with those measured by Herrmann [1996] with the same collector type in the same area, for 1992, 1993 and 1994 (1.25; 0.85; 0.76 $t\ ha^{-1}\ yr^{-1}$, respectively). These two sets of data give an average deposition rate of 1.00 $t\ ha^{-1}\ yr^{-1}$ for 1996 to

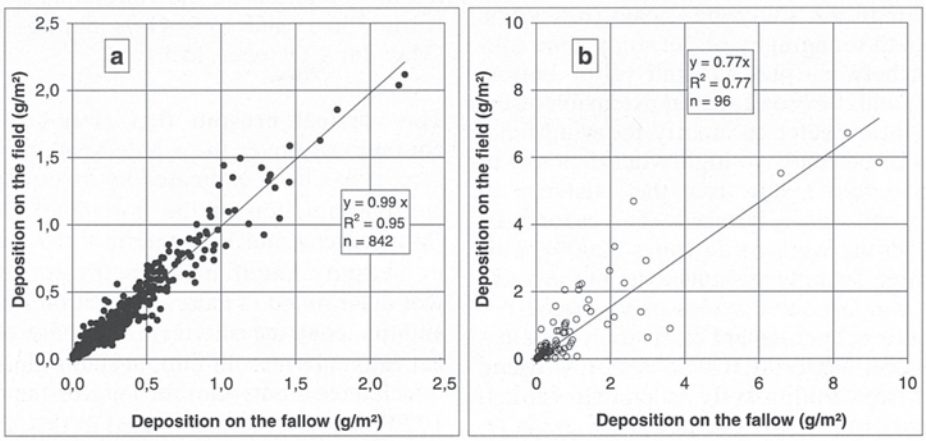

FIG. 2. – Total mass of sediments (uncorrected for particles > 20 µm) deposited on the field versus on the fallow (a) without rainfall, (b) with rainfall.
FIG. 2. – *Masses totales de sédiments (non corrigées des particules > 20 µm) déposées chaque jour dans le champ en fonction des masses de sédiment déposées dans la jachère* (a) *sans pluie*, (b) *avec pluie.*

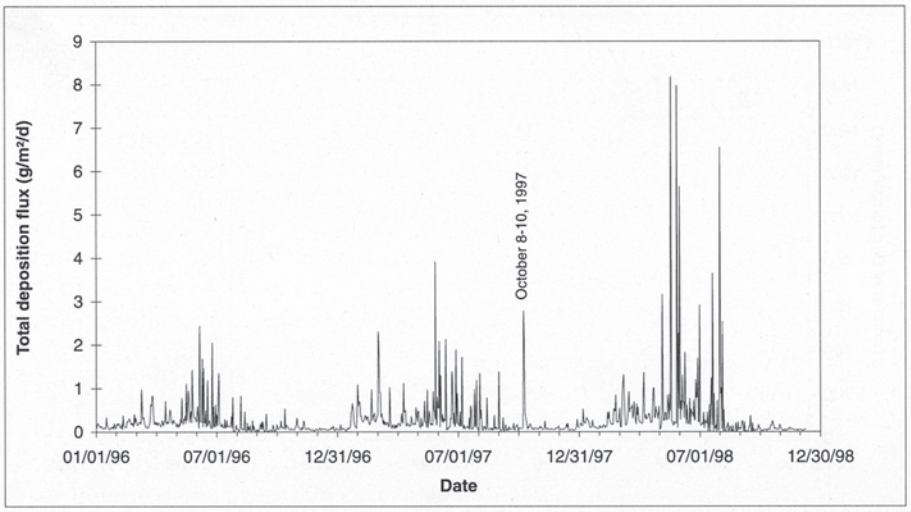

FIG. 3. – Seasonal trend of total mass deposition (g m^{-2} d^{-1}) during the 1996 to 1998 years as measured by passive CAPYR collector in fallow.
FIG. 3. – *Variation saisonnière de la masse totale de poussières déposée (g m^{-2} j^{-1}) pendant la période de mesure (1996-1998) mesurée grâce au capteur passif (CAPYR) installé dans la jachère.*

1998 and 0.95 t ha^{-1} yr^{-1} for 1992 to 1994. They were smaller than the 2.00 t ha^{-1} yr^{-1} average values found for years 1987 to 1989 in the same area by Drees *et al.* [1993], but clearly these authors have collected more locally produced coarse sediments in their traps as it is apparent from their measured particles size.

Erosion

Contrary to the continuous deposition that occurred every day of the year, erosion could be observed during short outbreaks of several hours at best (fig. 4a and b). The horizontal flux showed a clear seasonal cycle. Most of the erosion occurred in May and June at the onset of the rainy season (fig. 4a and b). There was no important event during the Harmattan season nor during the second part of the rainy season when litter or standing vegetation (pearl millet) provided enough ground cover protection for the soil surface. However, the frequency and the intensity of the events are highly variable from year to year.

Although horizontal fluxes were calculated from only four points of measurement in each land use type, we tried to estimate the spatial variability of horizontal fluxes for each land use type by calculating the coefficients of variation of horizontal flux for each particular storm. It varied in the field from 8 to 128 % during the 3 years. It reached a maximum in March/April and in August/September (mean value of 75 %) when spatial variability due to vegetation cover (litter and standing vegetation) was highest. For the 3 years, the mean value of this coefficient (58 %) was higher than the one (38 %) obtained by Sterk and Stein [1997] during 4 storms. These authors used 21 masts of sand catchers in an experimental pearl millet field with low spatial variability compared to a traditionally cultivated field. In the fallow, the mean value of the coefficient of variation, 59 %, was similar to that of the field. No time variation of this coefficient was obvious probably because the number of erosion events occurring in this area was too small (table I and fig. 4b).

Horizontal flux values ranged from 1 to 1,708 g cm^{-1} per event in the field (fig. 4a). The maximum value was similar to those obtained in the same field by Bielders *et al.* [2000] (2,400 g cm^{-1} per event) or to those measured with a different device in an experimental field (1,498 g cm^{-1} per event, Sterk and Stein [1997]). Even though we have only three years of data, the maximum values recorded each year suggested important inter-annual variability: one storm could produce a third of the total annual flux (table I). Thus, the annual quantity of sediment produced from a field could show high annual variations due to the occurrence of one or two major storms.

The total amount of sediment mobilized during the 3 years in the fallow was < 3 % of the one mobilized in the field (table I). Whereas 93 erosion events were recorded in the field, only 33 were observed in the fallow of which 23 occurred in 1996, representing 80 % of the total flux (fig. 4a and b, table I). This can be ascribed to an accidental fire which occurred in February 1996 and destroyed the grass litter early in the year. Nevertheless, it is noticeable that, despite the shrubs' protection (20 % of the surface was covered with *Guiera senegalensis* shrubs), slight erosion could be observed in the fallow, mainly in June, when the protection close to the soil surface was the lowest due to cattle grazing and litter consumption by termites.

Balance between erosion and deposition

Table II presents (i) the overall deposition flux corrected so as to take into account only particles < 20 µm and (ii) the vertical erosion flux computed from the horizontal flux using the transfer coefficient α. Figure 5 shows that the fallow received all year long more fine sediment than it produced. The same trend was observed for the field in 1997, but not in 1996 nor in 1998. In these latter cases, the quantities of sediments < 20 µm exported from the field in the vertical flux became higher than the quantities received after early June. The intensity of erosion was the main cause of annual variations in the field. In 1997 due to the lack of strong ero-

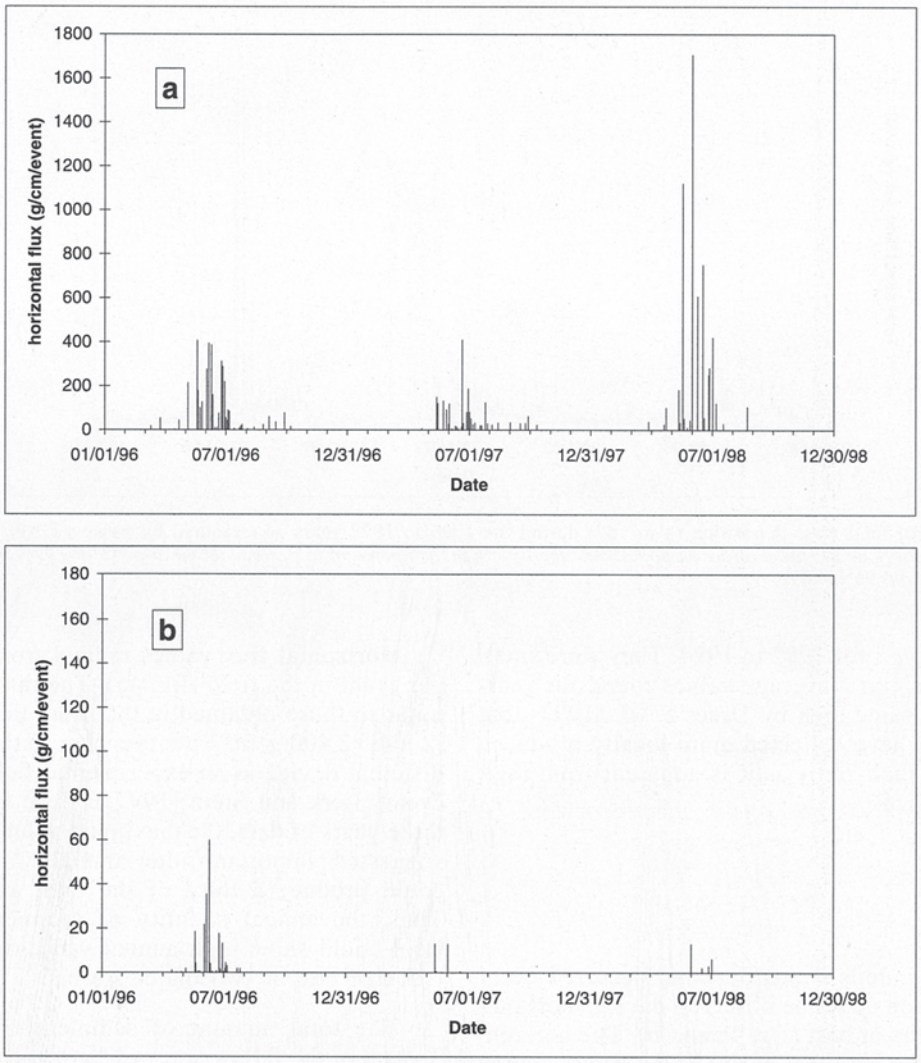

FIG. 4. – Seasonal trend of horizontal sediment flux (g cm^{-1} per event) during the 1996 to 1998 period (a) in the field, (b) in the fallow (Note that the Y-axis scale of the fallow plot is one tenth of the Y-axis scale for the field plot).
FIG. 4. – *Variation saisonnière du flux d'érosion horizontal (g cm^{-1} par événement) pendant la période de mesure (1996-1998)* (a) *dans le champ*, (b) *dans la jachère (à noter que l'échelle de l'axe des ordonnées du graphe de la jachère est le dixième de celle du graphe du champ).*

TABLE I. – Annual characteristics of wind erosion in the field and in the fallow: number of events, maximum and annual horizontal erosion flux.
TABL. I. – *Caractéristiques annuelles de l'érosion éolienne dans le champ et dans la jachère : nombre d'événements, flux horizontal maximum par événement et flux horizontal annuel.*

	Field			Fallow		
	nb of events	max. flux g cm^{-1}	annual flux g cm^{-1}	nb of events	max. flux g cm^{-1}	annual flux g cm^{-1}
1996	38	408	3894	23	60	201
1997	35	411	2094	5	13	28
1998	20	1708	6011	5	13	25

TABLE II. – Annual deposition and production of dust (size < 20 µm) according to the surface types (values for the plateau were estimated) and mass budget for the whole village land units and for the land suitable for cultivation alone (without taking into account plateau surface).
TABL. II. – *Dépôt de poussières annuel et production de poussières annuelle (< 20 µm) en fonction du type de surface (les quantités sont estimées pour les plateaux) et bilan de masse pour la totalité du terroir et pour les seuls sols cultivables (sans prendre en compte les plateaux).*

	deposition of particles < 20 µm t/ha	production of particles < 20 µm t/ha			mass budget of particles < 20 µm t/ha	
landscape unit	field, fallow, plateau	field	fallow	*plateau*	whole area	arable land
1996	0.53	0.66	0.03	*0*	0.25	0.19
1997	0.70	0.36	0.00	*0*	0.56	0.52
1998	0.89	1.02	0.00	*0*	0.48	0.38
mean	**0.71**	**0.68**	**0.01**	-	**0.43**	**0.36**
standard deviation	**0.18**	**0.33**	**0.02**	-	**0.16**	**0.17**
coefficient of variation (%)	**26**	**49**	**119**	-	**37**	**47**

sion events (fig. 4a), the rate of erosion was almost half of that of 1996 and a third of that of 1998 (table II).

The overall wind erosion balance for 1996 to 1998 was computed using the values obtained in the field and the fallow and weighting them by the percentages of fields (40 %), fallows (41 %) and plateaus (19 %) in the zone [Loireau *et al.*, 2000]. As mentioned earlier, it was assumed that wind erosion was nil on the plateau due to the presence of crusted soil and tiger bush. The balance was positive (table II), indicating thus a net yearly deposition, not only on the whole zone, but also on the arable land alone (field + fallow).

Apart from the spatial variability, a major source of incertitude in the estimation of the wind erosion balance lies

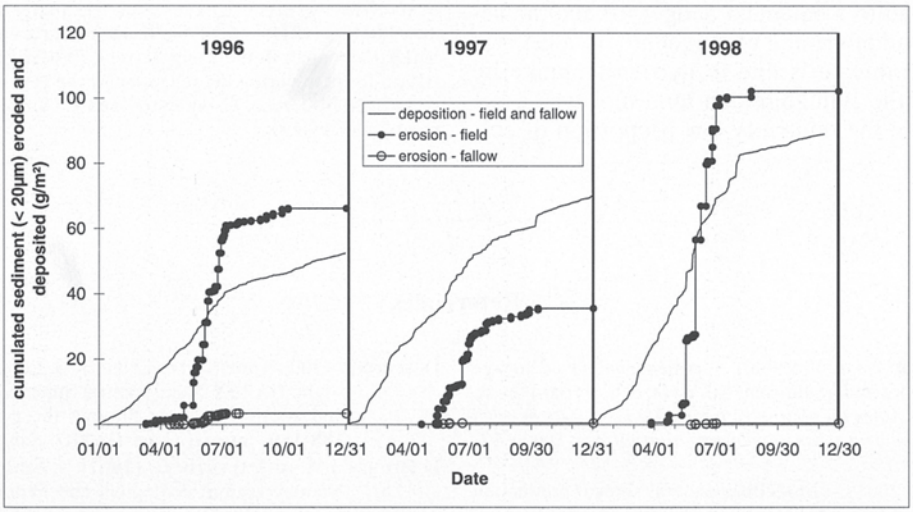

FIG. 5. – Cumulative mass of dust (size < 20 µm) deposited and exported from a field and from a fallow areas (1996, 1997 and 1998). Deposition rates are the same in the field as in the fallow.
FIG. 5. – *Masse de poussière (< 20 µm) déposée et exportée du champ et de la jachère cumulée sur chaque année de mesure (1996, 1997 et 1998). Les quantités déposées sur le champ et la jachère sont identiques.*

in the use of the transfer coefficient (α) for the calculation of the erosion vertical fluxes. A physically explicit dust production model (DPM) proposed by Alfaro and Gomes [2001] allows to compute (α) under various wind conditions. The computed values are in good agreement with the data of Gillette [1979]. Moreover these authors showed that α tends towards a value of 10^{-6} cm^{-1} for wind friction velocities above 40 cm s^{-1}. This result agrees with the value of 1.7 10^{-6} cm^{-1} chosen in this work because the major wind erosion events in the Sahel are linked to mesoscale convective systems that are characterized by high friction velocities.

Only few direct measurements of wind blown sediment mass budgets are available for the Sahel to compare with the budget calculated herein. For a similar village land unit located nearby, Chappell *et al.* [1998] obtained mean losses of 16 t ha^{-1} yr^{-1} over the last 30 years. These results have been obtained using the ^{137}Cs method and thus took water erosion also into account. Nevertheless because the hydrological units of the region are small endoreic areas [Desconnets *et al.*, 1997], soil losses can be ascribed only to wind erosion at this scale. This value of 16 t ha^{-1} yr^{-1} is not consistent with our results and even less so if one acknowledges that during the last 30 years, the percentage of cultivated fields has greatly increased at the expense of the fallows [Loireau *et al.*, 2001] implying maximum sensitivity to wind erosion at the present time. Under these circumstances, the mass budget calculated for 1996 to 1998 probably corresponds to the minimum value of the last 30 years (highest erosion rate), considering deposition rates as almost constant. This last assumption is substantiated by the dust deposition measurements over the last 10 years [Drees *et al.*, 1993; Herrmann, 1996]. Nevertheless, using the values obtained from 1996 to 1998, it is possible to calculate the sediment budget for arable land completely cultivated (without any fallow) in order to arrive at an estimate of the highest possible soil losses. The maximum sediment loss would have amounted to – 0.14 t ha^{-1} in 1998, but the mean over the 3 years 1996 to 1998 would have been almost balanced (+ 0.03 t ha^{-1} yr^{-1}). The budget value suggested from ^{137}Cs [Chappell *et al.*, 1998] seems to have been overestimated, perhaps due to the difficulties to obtain a precise estimate of the ^{137}Cs fallout inventory in the region [Chappell *et al.*, 1999].

At a larger scale, our results are in agreement with remote sensing observations which have revealed that the Sahelian area in the vicinity of the study zone was not a major source of dust emission throughout the period 1984-1993 [Legrand *et al.*, 1994].

CONCLUSIONS

This paper provides the first estimation of wind erosion budget at the scale of village land units based on direct and continuous monitoring over 3 years. The balance was calculated for the dust particles < 20 µm which are assumed to represent the overall aeolian sediments eroded or deposited at the study scale (25 km × 25 km).

The direct deposition measurements showed that the rate of deposition was the same on the cultivated field as on the fallow, hence on the whole study area. The direct measurement of horizontal airborne sediment fluxes clearly showed that wind erosion is related to land cultivation : fluxes in the fallow are always negligible compared to those in the field. Such aeolian dynamic – erosion in the fields and deposition in fallows – could be a major process in the nutrient cycle of the traditional land use system, in the absence of manure input, in the sandy Sahel.

The mass balance of wind erosion computed for an area 25 × 25 km^2 surrounding the village of Banizoumbou suggested that this area is currently a net deposition zone. This is due to the presence of fallows which occupy more than half of the arable land (without taking into account plateaus). But the current land use is now changing due to population increase leading to a decrease of the fallow surfaces and the fallow period duration. In this context, using the mean value calculated for the 1996 to 1998 period assuming constant deposition and erosion rates over time, it can be computed that replacing the fallow surfaces by culti-

vated fields would lead to a balanced budget for aeolian sediment over arable land alone and consequently to a general impoverishment of arable soils due to nutrients uptake by the crop. Up to now the Banizoumbou land unit was a net deposition zone due to the relatively low proportion of cultivated fields.

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