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Sediment and nutrient deposition in Lake Volta in Ghana due to Harmattan dust

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ABSTRACT

Harmattan is a dust-laden north-easterly wind that blows from the Sahara towards the Gulf of Guinea in the period November to March. It is the dominant wind in the north of Ghana while at the coast in the south it only occurs sporadically and here westerly or south-westerly winds dominate. Some of the dust is trapped in the vegetation, in lakes and other inland waters, and a little on the bare land. In this study, we determine the amount of sediment and nutrients that are deposited by this wind in big water bodies, exemplified by the dust deposition in the Harmattan period in the man-made Lake Volta. These depositions are compared with similar inputs by the rivers. On average, approximately 146,000 t of mineral matter and 42,000 t of organic matter are deposited per year in the Lake during the Harmattan periods. This is the equivalent of approximately 1% of the suspended sediment input by the rivers. The total amounts of Ca, P and Mg deposited during the Harmattan period are3000 t, 350 t and 810 t, respectively. About 40% of the Ca deposited is readily or plant available, for P and Mg it is about 50% and 20%, respectively. If the amount of readily available nutrients coming from the Harmattan dust is held against the influx of readily available (dissolved) Ca, Mg and P from the rivers to Lake Volta, it appears that the Harmattan dust accounts for only 0.7‰ Mg, 4.8‰ Ca, and 2.1% P. It must therefore be concluded that the contribution of nutrients to Lake Volta by the Harmattan dust is very limited.

1. Introduction

To generate hydro-electricity the Akosombo dam was built in the beginning of 1960's and Lake Volta, one of the largest man made reservoirs in the world, was formed. As time has passed, sedimentation is recognised as a potential problem in Lake Volta, for example in terms of the loss of water storage capacity and the role of sediment associated with nutrient loads (eutrofication) and contamination that lead to degradation of water quality and aquatic ecosystems (Akrasi, 2005). The assessments of the potential sediment problem, however, are hampered by limited information on the magnitude of the suspended sediment fluxes entering the lake. An estimation of the suspended sediment from Lake Volta's tributaries has been carried out by Akrasi (2005) but no estimations have been made on the influx of deposited dust to the lake.

In the southern part of West Africa, the dust-laden Harmattan wind is experienced from November to March, when the south westerly monsoon is replaced by a north eastern airflow from the Sahara. Storm activities in the Bilma and Faya Largeau area in the Chad basin raise large amounts of dust into the atmosphere, which is then carried southwest by the predominant wind, the Harmattan (Afeti and Resch, 2000; Cox et al., 1982; d'Almieda, 1986; Kalu, 1979; McTainsh, 1980; McTainsh and Walker, 1982). An enormous amount of dust is carried, deposited, re-suspended and re-deposited along the transportation path and when it reaches Ghana the dust is a mixture of dust from Sahara and dust collected along the transportation path (He et al., 2007). In December to February the Intertropical Convergence Zone (ITCZ) is located in the southern part of Ghana close to the coast of the Gulf of Guinea (Engelstaedter et al., 2006; Sunnu et al., 2008). Thus in the northern part of Ghana the NE-Harmattan wind dominates in November to March, while, in the south, it only occurs sporadically in shorter period and here the SW-monsoon still dominates (Engelstaedter et al., 2006).

Due to the great amount of material in suspension the Harmattan wind has a great impact on the agriculture, micro-climate, health, visibility and the ecosystem of a large area of West Africa, and even on the global environment (Aboh et al., 2009; Cox et al., 1982; Dionisio et al., 2010; Goudie and Middleton, 2006; McTainsh, 1980). Extensive research has been carried out on the Harmattan dust deposited in Nigeria and Niger (Adedokun et al., 1989; Drees et al., 1993; Møberg et al., 1991; Ramsperger et al., 1998), two countries that are closer to the dust source region of the Sahara than Ghana. In Ghana the literature on the Harmattan dust focuses mainly on the grain size distribution, mineralogy, rates of deposition and soil nutrients (Afeti and Resch, 2000; Awadzi and Breuning-Madsen, 2007; Breuning-Madsen and Awadzi, 2005; He et al., 2007; Resch et al., 2008; Sunnu et al., 2008; Tiessen et al., 1991).

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The purpose of this study is to derive reliable estimates of the input of aeolian sediments and its nutrients to Lake Volta and to compare the magnitude of these inputs with similar inputs from the rivers feeding Lake Volta.

2. Study area

Lake Volta in Ghana, Fig. 1, is dendritic in shape and has a generally north–south orientation with an average length and width of 400 km and 25 km respectively. It covers a surface area of 8502 km^2, has a catchment of 385,185 km^2, and the lake is mainly fed by the White and Black Volta Rivers. The catchment area stretches from approximately latitude 5°30′ N in Ghana to 14°30′ N in Mali, and from approximately longitude 5°30′ W to 2°00′ E in Burkina Faso. In the vicinity of Lake Volta the monthly mean temperature is rather uniform and between 25 °C and 30 °C throughout the year. In the south, two pronounced rainy seasons exist, one in April–June and the other in September–November. The minor dry season is in July–August, while the major dry season is from December–February. In the north there is only one rainy season from July to October, followed by a long dry season. The average annual precipitation in the north is approximately 1000 mm and the vegetation zone is mainly classified as the Guinea savannah, Fig. 1, with grasses, scrubs and a few trees (Dickson and Benneh, 1995). In the south east a minor part can be classified as moist semi-deciduous tropical forest with a mean annual precipitation of approximately 1500 mm, otherwise it is classified as the coastal savannah zone with an annual precipitation less than 1000 mm, Fig. 1.

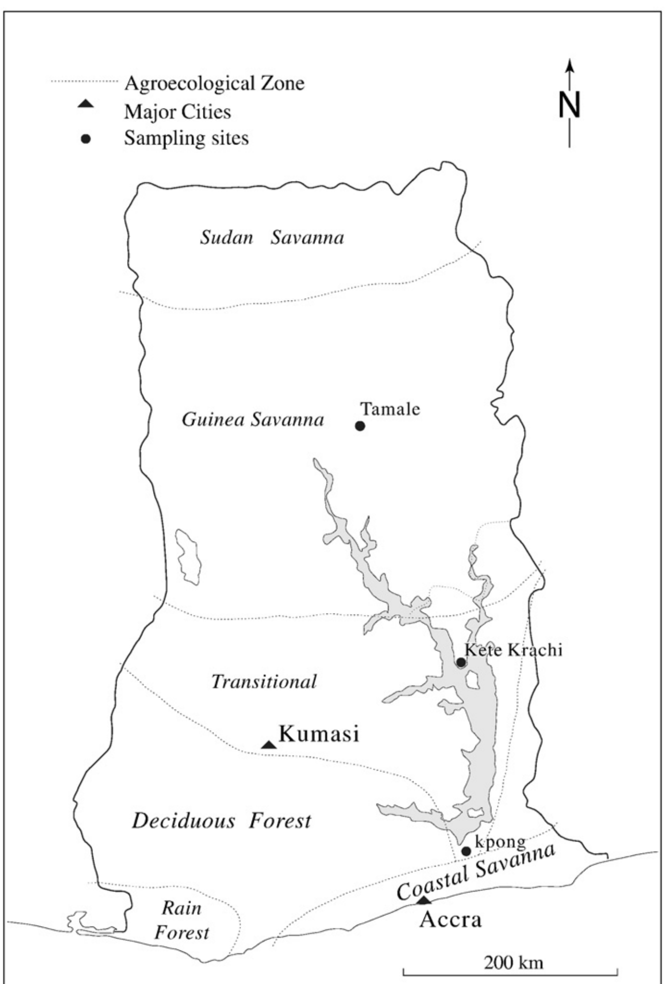

Fig. 1. Location of Lake Volta and sampling sites.

3. Sampling methods

In the period 2000 to 2007, Harmattan dust has been collected at 4 to 12 locations all over Ghana (Awadzi and Breuning-Madsen, 2007). In order to determine the sediment and nutrient deposits in Lake Volta, the three stations closest to the lake are used: Tamale, Kete Krashi and Kpong, Fig. 1. At three stations dust was also collected from March to November 2007 in order to compare the amount of dust deposited within and in between the Harmattan seasons. Two of the sites, Kete Krashi and Kpong, are located close to the Volta Lake. On the contrary, Tamale is not located close to the lake, but it is the sampling site closest to the northern part of the lake. The sampling sites at Tamale and Kpong are situated at agricultural experimental stations and at Kete Krashi on a public property, and are all placed far from public roads in order to minimise the amount of local dust. The sampling sites are all covered with grass. Table 1 shows the area and the percentage of Lake Volta that is covered by the three sampling sites determined by the nearest neighbour method.

Two different types of samplers, Fig. 2, are used for calculating the amount of mineral and organic dust retained in the lake as well as the total amount of nutrients and its availability. Bowls with water simulate the lake surface and therefore the dust retained in the bowls is a rough estimate of the dust retained by a water surface. However, due to algal blooms the content of organic matter in the bowls is too large and the proportion of the readily and slowly available nutrients will not be correct. Thus the dust on the mat sampler is used for measuring the proportions of organic matter and nutrients in the dust, while the bowls with water are used to determine the total amount of dust deposited.

The specification of the two samplers is as follows:

1. Plastic bowls about 40 cm deep with an inlet area of 0.23 m^2 and 0.26 m^2. The bowls were filled with distilled water to within 10 cm of the top, and the water level was topped up every week. In order to prevent birds, mice and other animals from drinking and polluting the water, a thin 1 cm mesh was used to cover the mouth of the bowls.
2. Plastic mats comprising plastic straws simulating a grass lawn. There were eight plastic straws per square centimetre, each straw being 1.5 cm long with a surface area of about 1 cm^2. The plastic mat simulated a surface area about eight times that of bare ground. Two types of set ups were used. In the north at Tamale, mats were placed on plates of plywood, 70 cm wide and 90 cm long, surrounded by a 2 cm high wooden frame. In order to drain the water from the occasional showers that occur during the Harmattan season, a drain was made by connecting a tube to a hole drilled in the frame. The tube led the water to a 36 l plastic container. In the south (Kete Krachi and Kpong), each mat was placed on a circular plate of plywood that was placed 1 cm below the top of a bowl. Holes were made in the plywood to ensure good drainage from the mat during erratic showers.

The samplers were all placed 1 m above the ground. For each Harmattan period the sampling began about December 1st and ended the following year at the end of February (Kpong and Kete Krashi) or in the beginning of March (Tamale). At the end of the

Table 1
The percentage share and area in km^2 of Lake Volta covered by three sampling sites, Tamale, Kete Krashi and Kpong calculated by the nearest neighbour method.

Location	% of Volta Lake	Volta Lake km^2
Kpong	26.0	2211
Kete Krashi	58.6	4982
Tamale	15.4	1309
Total	100.0	8502

a

b

Fig. 2. Picture of the bowl and mat sampler (a) and bowl-mat (b) used at the sampling sites.

sampling period, the samplers were emptied. When emptied, the mats were sealed in plastic bags to avoid contamination during transportation to the laboratory in Accra. Most of the water in the bowls was decanted on site and the remaining water with the sediment was stored in 1.5 l plastic bottles. Furthermore, despite the covering net a lot of dead insects were floating in the water contaminating the sample. The distilled water in the bowls had turned green making it obvious that biological activity had taken place.

3.1. Discussion of sampling method

In other investigations, dust samples have been collected in many ways, but mostly in different types of containers or funnels; some dry, others filled with water or liquid paraffin (Adetunji et al., 2001; McTainsh and Walker, 1982; McTainsh et al., 1997; Ramsperger et al., 1998; Tiessen et al., 1991) or on different types of plates (Breuning-Madsen and Awadzi, 2005; Goossens and Rajot, 2008; Møberg et al., 1991; Tiessen et al., 1991). The question is which sampling technique gives the most accurate measure of the amount of dust that settles on the landscape. For instance, Stoorvogel et al. (1997) showed that in the tropical rain forest in the Taï National Park in Ivory Coast, the Harmattan dust deposition was twice as high using a canopy drip method compared to the dust captured in a wet basin. This shows that the dust samplers should express the land surface cover as much as possible. This was also clearly shown by Breuning-Madsen and Awadzi (2005) who investigated the relationship between different samplers with different types of surfaces (water, plastic grass lawn and hard plain surfaces) and the dust that settled. In 2001, the amount of dust retained at Bawku by the bowls was 15.9 g/m^2 and by the mats 15.7 g/m^2. The year after the figures were 80.7 g/m^2 and 24.7 g/m^2, respectively, while in 2003 it was 30.7 g/m^2 and 18.7 g/m^2, respectively. As the samplers were standing close to each other, it can be assumed that the particle density in the atmosphere was the same at the different samplers. This shows that it is very difficult to develop models that predict the dust deposition based on the particle density in the atmosphere measured directly or by satellite images. This was for example done by Resch et al. (2008) in Ghana who based on measured particle densities in the air, calculated the deposition rate at Kumasi and Tamale without taking the type of surface into consideration.

In order to determine the dust retained in Lake Volta, samplers with water surfaces must be used. However, when sampling dust in water, contamination of the sample due to bird droppings, drowned insects and algal bloom is most likely to occur. Especially the algal bloom is a problem as it increases the amount of organic matter and incorporates inorganic plant available nutrients in organic matter. Furthermore, it is possible to loose some nutrients due to the decanting procedure when collecting the sample. Those problems are not present when using the mat samplers, but the mat sampler does not mirror the surface of the lake. Thus, in order to secure the most reliable result on dust deposition on a lake surface, it was decided to combine the two sampling methods described in Section 3. The bowl gives an estimate of mineral dust deposited in the lake and the dust deposited on the mats is used for determining the organic matter and the chemical composition of the dust. Both sampling methods might be affected by aerodynamic problems around the samplers that might introduce minor differences compared to the dust deposition in the lake (Goossens and Rajot, 2008).

4. Analyses

In the laboratory, the mats were carefully washed with distilled water. The water was evaporated in big glass beakers in order to get a dry dust sample for analyses. The bowl samples were also evaporated in big glass beakers. Farming activity in the vicinity of the sampling sites had contaminated the samples with remnants of straw and starch. These remnants were removed together with dead insects by a floating procedure: the samples were put in water, and then the macro organic matter like straw and insects floating in the surface water could be removed physically.

Because only small amounts of dust were collected, analytical procedures involving small amounts of soil material were chosen. Alternatively, standard procedures were modified, reducing the amounts of sediment and extraction liquids, but keeping the ratio the same as in the standard procedure.

Total organic carbon (TOC) was analysed using the dry combustion method at 1.250 °C in oxygen on an Eltra SC-500 analyzer, with an accuracy of $\pm$0.2% (ELTRA, 1995). Plant or readily available P was determined by the bicarbonate method (Olsen and Sommers, 1982), and readily available Ca and Mg were determined by Atom Absorption Spectrophotometry (AAS) after extraction with 1 M ammonium acetate. Total P and total non silicate-bound Ca and Mg (hereafter referred to as total P, Ca, and Mg) were determined as follows: The organic matter was reduced to ash in an oven at

550 °C, followed by a treatment with 6N H_2SO_4 at 80 °C for 1 h and washed several times through a filter using distilled water. The total amount of phosphorus in the extracts was determined spectrophotometrically by the molybdenum-blue method (Kuo, 1996) and the total amounts of non silicate-bound Ca and Mg (in the extracts) were determined by AAS. The amounts of slowly available P, Ca and Mg were determined as the difference between the total and the readily available P, Ca and Mg. Slowly available nutrients are mainly organically bound nutrients that only will be readily available for plants after mineralization of the organic matter.

Texture was determined by use of a Malvern Mastersizer 2000 (laser diffraction method) as this method requires only a small amount of soil material, less than 1 g of dust samples. The samples were washed in hydrochloride acid for removal of carbonates if present and treated with hydrogen peroxides for removal of organic matter. The samples were prepared with 0.1 M $Na_4P_2O_7$ and treated with ultrasound for 3 min before analysis. The analysis was performed using a standard operation procedure for operating the Malvern Mastersizer 2000 and, finally, the diffraction pattern was converted to a grain size distribution using Mie diffraction theory (Agrawal et al., 1991; Operators Guide, 1998). The mean grain size was determined by the moment method (Davis, 1986).

4.1. Discussion of analysis

The amount of nutrients deposited by the dust will be more or less plant available. The nutrients in the dust that are part of readily soluble salts or retained as exchangeable cations on particle surfaces are readily available. These are normally determined by treating the soils with 1M NH_4Ac (ammonium acetate). Part of the nutrients will not be readily available, but might be plant available with time. These are, for example, the nutrients stored in organic matter which might decay due to oxidation or changes in pH, and P fixed in iron and aluminium oxides (at low pH) or Ca (at high pH). In the present paper, the determination of the total available nutrients is done by treating the soil samples with warm 6N H_2SO_4 after heating the samples at 550 °C. This method is debatable due to the heating and the use of warm 6N H_2SO_4 as it might attack some silicates; especially clay minerals. This might give too high values of nutrients, but the liberation of nutrients from the breakdown of the silicate lattice must be minimal compared to the nutrients liberated from the breakdown of the organic matter. Thus we find that the H_2SO_4-methods could be a reasonable estimate of the total amount of nutrients present, but an alternative method using H_2O_2 instead of heating the samples for decomposition of organic matter might be a better method. However, H_2O_2 might not break down all organic matter.

5. Results and discussion

Fig. 3 shows the concentration of carbon in the bowls and on the mats at the sampling sites used in the nation-wide sampling of Harmattan dust in the four sampling periods 2002 to 2006. In total, a dataset of 26 observations on concentrations of carbon in the bowls and on the mats was available. The average of the 26 observations was 23.8% carbon in the bowls and 11.1% carbon on the mats. Thus the concentrations of carbon in the bowls were about the double of those on the mats. The concentrations of carbon were low in the north where the north east wind dominates, while it was high in the south where the south westerly winds dominate. The reason for the higher concentration of carbon in the bowls compared to the mats can be explained by algal blooms in the bowls due to input of nutrients from the dust and by insects that had been caught in the water. The algal bloom makes the total amount of dust that is retained by the bowl too high due to the increase in organic matter. Thus the mass of dust that is retained by the bowl must be corrected so its content of organic carbon is equal to the amount of organic carbon on the mat. The correction of the amount of sediment that is retained by the bowl can be calculated by the following formula, if we assume that organic carbon makes up 58% of organic matter (Brady and Weil, 2002):

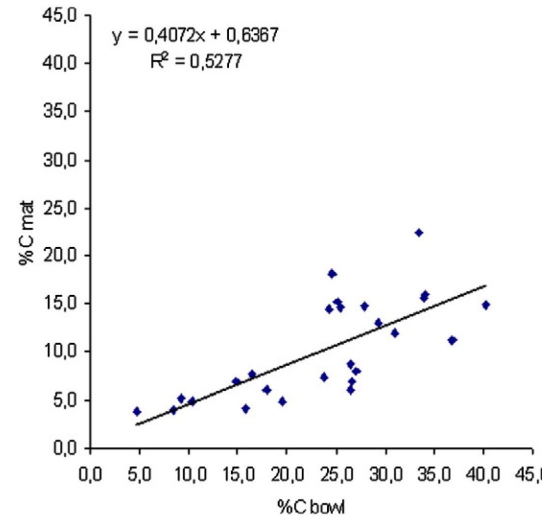

Fig. 3. The relationship between% C in bowl samples and mat samples from different sampling sites in Ghana in 2002–2006. $y = 0.4072x + 0.6367$ $R = 0.7264$ $n = 26$ significant level = 99.95%.

$$A\ corr. = (A–(A * B/100)) * (100/(100-C))$$

A mass of dust in the bowl
B % organic matter in the bowl calculated as: %C (bowl) * 100/58
C % organic matter on the mat calculated as: %C (mat) * 100/58.

Table 2
Amount of dust, organic carbon content and texture in bowls and on mat at three sampling sites Tamale, Kete Krashi and Kpong in the Harmattan seasons from 2002 to 2004 and 2005–2007.

Location	Year[a]	Bowl				Mat		
		Dust	Dust corrected	Org. C	Texture mean	Dust	Org. C	Texture mean
		t km^{-2}	t km^{-2}	%	µm	t km^{-2}	%	µm
Tamale	2003	43	26	26.5	11.7	14	6.0	16.2
	2004	25	19	17.9	9.2	12	6.0	12.3
	2006	35	35	5.1	[b]	12	5.5	[b]
	2007	28	25	11.3	8.6	16	5.3	13.1
	Average	33	26	15.2	9.8	13	5.7	13.9
	Std.	8	7	9.2	1.7	2	0.4	2.1
Kete Krashi	2003	47	33	33.4	11.6	11	22.4	11.6
	2004	28	16	34.0	8.6	5	15.6	9.5
	2006	18	17	17.9	[b]	11	14.6	6.7
	2007	35	35	8.3	11.2	14	8.0	8.6
	Average	32	25	23.4	10.5	10	15.1	9.1
	Std.	12	10	12.5	1.6	3	5.9	2.0
Kpong	2003	17	14	24.6	6.6	5	18.2	7.7
	2004	29	18	29.4	10.6	10	13.0	6.1
	2006	11	9	19.5	[b]	10	12.0	[b]
	2007	11	10	10.6	6.0	3	8.7	13.1
	Average	17	13	21.0	7.7	7	13.0	9.0
	Std.	8	4	8.0	2.5	4	3.9	3.6

[a] Year of harvest.
[b] Not measured.

The influx of nutrients by insects is extremely low due to the floating procedure, but the algal bloom in the bowls will change the ratio between readily available and slowly available nutrients by incorporating inorganic water soluble calcium, magnesium and phosphorus in the organic matter. Hereby readily available nutrients are turned into slowly available nutrients that can only be made readily available again after decomposition of the organic matter. Therefore it was decided to use the nutrient data determined on the mat samples in combination with the corrected masses from the bowl samples when calculating the nutrient input to Lake Volta.

The amount of dust, the contents of organic carbon and the texture in bowls and on mats at the three sampling sites in the Harmattan seasons from 2002 to 2007 (except for the season 2004–2005), are given in Table 2. The dust deposition is 26 ($\pm$7) t km^{-2} in Tamale, 25 ($\pm$10) t km^{-2} in Kete Krashi, while it is 13 ($\pm$4) t km^{-2} in Kpong, which is about half of the amount compared with the two other locations. This is in line with Ramsperger et al. (1998) who stated that the dust influx decreases from the North to the South and with Resch et al. (2008) who estimated the deposition rate between Kumasi and Tamale to be 13 t km^{-2} in 2002 and 31 t km^{-2} in 2005. From the high standard deviation and Table 2 it is seen that the amount of dust deposited varies from year to year. The year of maximum dust deposition among the three sampling sites varies too; in Tamale it was 2006, in Kete Krashi 2007 and in Kpong 2004. This corresponds to the results of Awadzi and Breuning-Madsen (2007) who investigated the deposition rate and texture of the dust in the Harmattan periods from 2000 to 2005 based on 9 stations covering Ghana. Awadzi and Breuning-Madsen (2007) also found a variation of dust deposited from year to year and it is therefore suggested that there is a high input of local dust and that the local climatic conditions, such as vertical eddies, have a great influence on the amount of dust deposited locally. In Tamale about 10% of the dust collected on the mat sampler is organic matter (5.7% C) and it increases towards the south to about 25% organic matter in Kete Krachi (15.1% C) and Kpong (13.0% C). The relative increase in the content of organic carbon between north Ghana and mid/south Ghana might be due to differences in the sedimentation rate of the mineral and organic parts of the dust from outside Ghana, an enrichment of dust with organic matter due to bush fires when it passes Ghana or differences in the concentration of organic matter in the local dust. Concerning the texture of the samples, the average mean grain size is about 10 μm, the coarsest mean texture being in the north (Tamale). This corresponds to the finding of Awadzi and Breuning-Madsen (2007) who found decreasing mean grain sizes from 13 μm in the north (Bawku) to 5 μm in the south (Kade). This is more coarse grained than published by Sunnu et al. (2008) who used an optical particle counter at Kumasi and determined an 8 year average of 1.5 μm. The difference might be due to the fact that Awadzi and Breuning-Madsen determined the grain size of the settled dust smaller than 200 μm, while Sunnu et al. (2008) determined the grain size of dust in suspension and only measured the grain size of the dust in the range of 0.5 μm to 25 μm. In Tamale and Kpong the texture of the dust on the mats is coarser than the dust in the bowls, the opposite is observed in Kete Krashi. This is in line with Breuning-Madsen and Awadzi (2005) who found no consistent difference in the mean grain size between bowls and mats at four sites in Ghana.

Concentrations of total and readily available Ca, Mg and P in the dust are shown in Table 3 together with the total amounts of nutrients in kg km^{-2}. Ca is the dominant nutrient in the dust. The concentration of total Ca is 19‰ in Kete Krashi and 10‰ and 12‰ in Kpong and Tamale, respectively. On average, about half of the total Ca is readily available, highest in Kpong with about 2/3 and lowest in Kete Krashi with 2/5. The total Mg concentration is between the total concentrations of Ca and P, but closest to P. Total Mg varies between 2.0‰ and 5.5‰, highest in Kete Krashi and lowest in Tamale. The Mg is less readily available than the Ca since only about 1/3 of the total Mg in Kpong is readily available, while in Kete Krashi and Tamale only about 1/5 is readily available. Total P is low compared to the two other nutrients and varies between 2.4‰ in Kpong and 1.3‰ in Tamale. About half of total P in Kete Krashi and Kpong is readily available and approximately 1/3 in Tamale. In total Kete Krachi has the highest concentration of nutrients (26.4‰) and Tamale and Kpong have approximately the same total concentration of the nutrients investigated (15‰).

The deposition of the nutrients in kg km^{-2} shows the highest values for Kete Krashi and lowest for Kpong, Table 3. On average, the total amount of Ca deposited in Kete Krashi is 463 kg km^{-2}, while the total amount of Ca deposited in Tamale is 315 kg km^{-2} and in Kpong 122 kg km^{-2}, which is the equivalent to about 70% and 25%, respectively, of the amount in Kete Krashi. The total amounts of Mg and P at Kete Krashi are 125 kg km^{-2} and 47 kg km^{-2}, respectively, at Tamale

Table 3
NH_4-Ac extractable Ca and Mg, bicarbonate extractable P and H_2SO_4 extractable Ca, Mg and P in ‰ and in kg km^{-2} at three sampling sites Tamale, Kete Krashi and Kpong in the Harmattan seasons from 2002 to 2004 and 2005–2007.

Location	Year[a]	NH_4-Ac extractable Ca and Mg and bicarbonate extractable P						H_2SO_4 extractable Ca, Mg and P					
		Ca	Mg	P	Ca	Mg	P	Ca	Mg	P	Ca	Mg	P
		‰	‰	‰	kg km^{-2}	kg km^{-2}	kg km^{-2}	‰	‰	‰	kg km^{-2}	kg km^{-2}	kg km^{-2}
Tamale	2003	9.6	0.1	0.3	247	2	7	14.8	2.3	1.3	382	59	33
	2004	5.3	0.5	0.4	102	10	8	7.9	1.6	1.1	151	31	21
	2006	3.8	0.5	0.6	134	17	22	11.6	2.7	2.1	409	93	74
	2007	3.4	0.5	0.4	84	12	9	12.8	1.5	0.8	318	36	20
	Average	5.5	0.4	0.4	142	10	11	11.8	2.0	1.3	315	55	37
	Std.	2.8	0.2	0.1	73	6	7	2.9	0.6	0.6	116	28	25
Kete Krashi	2003	10.7	0.2	0.6	350	6	19	24.5	5.3	0.7	804	173	23
	2004	6.9	0.3	1.6	112	5	26	13.0	3.1	2.5	211	50	41
	2006	5.6	1.8	[b]	93	31	[b]	28.7	10.8	7.5	477	180	125
	2007	5.6	1.1	0.9	196	39	32	10.3	2.8	2.2	361	98	78
	Average	7.2	0.9	1.0	188	20	26	19.1	5.5	3.2	463	125	67
	Std.	2.4	0.8	0.5	117	17	6	8.9	3.7	3.0	252	62	45
Kpong	2003	12.8	0.4	1.7	178	6	24	11.4	3.2	2.6	158	45	36
	2004	4.6	1.5	1.0	83	26	18	8.2	5.2	2.9	148	95	52
	2006	2.8	1.6	[b]	27	15	[b]	10.3	5.2	4.0	98	49	38
	2007	3.5	1.5	0.5	36	15	6	8.4	1.9	1.8	85	19	18
	Average	5.9	1.2	1.1	81	16	16	9.6	3.9	2.8	122	52	36
	Std.	4.6	0.6	0.6	69	8	9	1.5	1.6	0.9	36	31	14

[a] Year of harvest.
[b] Not measured.

55 kg km^{-2} and 37 kg km^{-2}, respectively, and at Kpong 52 kg km^{-2} and 36 kg km^{-2}, respectively. In total, Kete Krashi has about the double amount of Mg and slightly more P compared to the two other locations. The readily available content of Ca is at Kete Krashi 188 kg km^{-2}, at Tamale 142 kg km^{-2} and at Kpong 81 kg km^{-2}. The amounts of readily available Mg and P are at Kete Krashi 20 kg km^{-2} and 26 kg km^{-2}, respectively, at Tamale 10 kg km^{-2} and 11 kg km^{-2}, respectively and at Kpong 16 kg km^{-2} for both Mg and P.

5.1. Comparison of the input of dust and river sediment to Lake Volta

The amount of mineral dust, organic matter, total, slowly and readily available Ca, Mg and P deposited in Lake Volta can be calculated (Table 4). The calculations are based on the areas of Lake Volta that are covered by Tamale, Kete Krashi and Kpong, respectively (Table 1), the amount of corrected dust, the percentage of organic carbon (Table 2) and the amount of nutrients per km^2 (Table 3).

Table 4 shows that on average Lake Volta receives about 188$*10^3$ t of total dust per year during the Harmattan period and about 42$*10^3$ t of organic matter. This can be compared to the input of suspended material to Lake Volta by rivers. Akrasi (2005) has made an estimation of the yearly influx of suspended sediment by the rivers to Lake Volta. The estimation is based on measured data on suspended sediment in rivers and model calculation. The study showed that the mean annual suspended sediment input into Lake Volta was roughly 17$*10^6$ t year^{-1}. Thus, the Harmattan dust deposition in Lake Volta corresponds to approximately 1% of the suspended sediment input by the rivers.

From Table 4 it furthermore appears that about 3000 t of total Ca is deposited in the lake, and less than half of that is readily available (1300 t Ca). The dust contributes with approximately 810 t of total Mg and 350 t of total P. Only less than 1/5 of the Mg is readily available, while about half of the P is readily available for the plants. The amount of nutrients coming to Lake Volta from Harmattan dust seems relatively high, but compared with the inflow of nutrients by the rivers that flow into Lake Volta it is quite low. Andah et al. (2003) have modelled the inflow of water to the lake and find an annual inflow of about 40 km^3. Based on water samples collected at Oti River and Black, White and lower Volta in the period 1976–78 (Andah et al., 2003) the dissolved nutrients in the inflow water are about 6.8 mg l^{-1} for Ca, 5.2 mg l^{-1} for Mg and 0.6 mg l^{-1} for PO_4^{3-} or 0.2 mg l^{-1} P. This gives approximately 272,000 t Ca, 208,000 t Mg and 8000 t P. These types of nutrients can be compared to the readily available nutrients in the dust. It is therefore possible to estimate how much of the readily available nutrient input to the lake that can be ascribed to the dust in the Harmattan season. The Harmattan dust input of Ca is about 4.8‰ of the annual input by the rivers and for Mg it is about 0.7‰. P is a relatively major input and the dust corresponds to 2.1% of the P input from the rivers.

Table 4
Estimated sediment, organic matter, total and easily available Ca, Mg, K and P deposited in the Lake Volta in the Harmattan periods from 2002 to 2004 and 2005–2007.

Year[a]	Total dust	Mineral dust	Org. matter	NH_4-Ac extractable Ca and Mg and bicarbonate extractable P			H_2SO_4 extractable Ca, Mg and P		
				Ca	Mg	P	Ca	Mg	P
	10^3 t	10^3 t	10^3 t	10^3 t	10^3 t	10^3 t	10^3 t	10^3 t	10^3 t
2003	228	152	76	2.46	0.05	0.16	4.85	1.04	0.24
2004	146	113	33	0.88	0.10	0.18	1.58	0.50	0.35
2006	150	121	29	0.70	0.21	[b]	3.13	1.13	0.80
2007	229	199	30	1.17	0.24	0.18	2.40	0.58	0.46
Average	188	146	42	1.30	0.15	0.17	2.99	0.81	0.46
Std.	47	39	23	0.80	0.09	0.01	1.39	0.32	0.24

[a] Year of harvest.
[b] Not measured.

5.2. The input of dust to the Lake Volta from outside the Harmattan period

A pilot study of dust collected in bowls outside the Harmattan periods in 2007 at three stations in Ghana, Tamale, Kpong and Kade, Table 5, has showed that the deposition of dust outside the Harmattan period from March to November is the same size as within the Harmattan period. The dust deposition in the Harmattan period 2006–07 is rather low, from 27.9 t km^{-2} at Tamale to 10.5 t km^{-2} at Kade, and the dust deposition in the following 9 months until the next Harmattan period is higher, from 42.8 t km^{-2} at Tamale to 32.4 t km^{-2} at Kade. The Harmattan period 2007–08 is much richer in dust than 2006–07 and the dust deposition was ranging from 48.0 t km^{-2} at Tamale to 17.2 t km^{-2} at Kade. If we compare the average dust deposition of the two Harmattan periods with the intervening period, the total dust deposition in the period outside the Harmattan is slightly bigger although the dust deposition rate is highest during the Harmattan period due to the shorter time period. It must therefore be expected that a calculation of the amount of sediment deposited by dust in Lake Volta based alone on the dust deposited during the Harmattan period will underestimate the total amount of sediment deposited by dust by at least a factor 2. Consequently, it can be expected that the dust in general will account for approximately 2% of the input of suspended sediments to Lake Volta. It must therefore be expected that a calculation of the amount of nutrients deposited by dust in Lake Volta based on the dust deposition in the Harmattan period alone will underestimate the yearly total amount of nutrients deposited by dust. The content of nutrients in the dust deposited outside the Harmattan has not been measured, but based on the results by Chester et al. (1972), He et al. (2007) and Lyngsie et al. (2011) the Harmattan dust has a substantial input of local dust. Thus if we anticipate that the dust outside the Harmattan period will have a content of nutrients rather close to the dust deposited during the Harmattan period, Lake Volta receives a nutrient content about the double of the amount measured in the Harmattan period. Thus a rough estimate will be that compared to the water soluble inflow of nutrients by the river, the yearly dust deposition will account for about 4% of the water soluble P to the lake, while Ca will account for about 1% and Mg about 1.5‰.

The comparison of the sediment contribution to Volta Lake by aeolian material and from river sediments is based on measured data and models. The comparison shows that the contribution by dust is limited. The determination of the influx of nutrients by the river is

Table 5
The dust deposition in bowls with water at three stations: Tamale, Kpong and Kade in the Harmattan period. Kade (6158 N, −0921 E) is located between Accra and Kumasi. Deposited dust not corrected for organic matter.

Location	Period	Date of harvest	Number of days	Deposited dust	Deposition rate
				t km^{-2}	t km^{-2} day^{-1}
Tamale	Harmattan	Dec. 2006–Mar. 2007	110	28	0.25
	Outside Harmattan	Mar.–Nov. 2007	255	43	0.17
	Harmattan	Dec. 2007–Feb. 2008	90	48	0.53
Kpong	Harmattan	Dec. 2006–Feb. 2007	87	11	0.13
	Outside Harmattan	Mar.–Nov. 2007	278	39	0.14
	Harmattan	Dec. 2007–Feb. 2008	83	44	0.53
Kade	Harmattan	Dec. 2006–Feb. 2007	88	11	0.12
	Outside Harmattan	Mar.–Nov. 2007	277	32	0.12
	Harmattan	Dec. 2007–Feb. 2008	84	17	0.20

problematic as only few data is available on the input of soluble nutrients to the lake and information on the nutrient content linked to the suspended materials is absent. The comparison of the nutrient input by the dust and river water is therefore very uncertain and may even overestimate the importance of the dust contribution. Finally, the importance of the dust deposition outside the Harmattan period should be investigated further, as well as the share of long transported dust and local dust in the dust deposited.

6. Conclusion

Based on the results and discussion in the previous paragraphs it can be concluded that the aeolian sediment deposition in the Volta Lake is insignificant compared to the sediment deposition by the rivers, and the aeolian dust accounts for far less than 1% of the sediment deposited in the Lake. According to the nutrient input to the Lake it must also be concluded that the input by the aeolian activity is insignificant compared to the input by the rivers. Thus the sedimentation of the man-made lake and the eutrofication of the water body are of mainly fluvial origin and the influence of the aeolian dust is neglectable.

References

Aboh, I.J.K., Henriksson, D., Laursen, J., Lundin, M., Ofosu, F.G., Pind, N., Lindgren, E.S., Wahnström, T., 2009. Identification of aerosol particle sources in semi-rural area of Kwabenya, near Accra, Ghana, by EDXRF techniques. X-Ray Spectrometry 38 (4), 348–353.

Adedokun, J.A., Emofurieta, W.O., Adedeji, O.A., 1989. Physical, mineralogical and chemical properties of Harmattan dust in Ile-Ife. Nigeria. Theoretical and Applied Climatology 40, 161–169.

Adetunji, M.T., Martins, O., Arowolo, T.A., 2001. Seasonal variation in atmospheric deposition of nitrate, sulphate, lead, zinc, and copper in southwestern Nigeria. Communications in Soil Science and Plant Analysis 32, 65–73.

Afeti, G.M., Resch, F.J., 2000. Physical characteristics of Saharan dust near the Gulf of Guinea. Atmospheric Environment 34, 1273–1279.

Agrawal, Y.C., McCave, I.N., Riley, J.B., 1991. Laser diffraction size analysis. In: Syvitski, J.M.P. (Ed.), Principles, methods and applications of particle size analysis. Cambridge University Press, New York, pp. 119–128.

Akrasi, S.A., 2005. The assessment of suspended sediment inputs to Volta Lake. Lakes and Reservoirs: Research and Management 10, 179–186.

Andah, W.E.I., Van de Giesen, N., Biney, C.A., 2003. Water, Climate, Food and Environment in the Volta Basin. Contribution to the Project ADAPT. www.weap21.org/download/AdaptVolta.pdf.

Awadzi, T.W., Breuning-Madsen, H., 2007. Harmattan dust deposited in Ghana within 2000–2005. West African Journal of Applied Ecology 11, 173–188.

Brady, N.C., Weil, R.R., 2002. The nature and properties of soil, 13th ed. Prentice Hall, New Jersey, pp. 498–595.

Breuning-Madsen, H., Awadzi, T.W., 2005. Harmattan dust deposition and particle size in Ghana. Catena 63, 23–38.

Chester, R., Elderfield, J.J., Griffin, J.J., Johnson, L.R., Padgham, R.C., 1972. Aeolian dust along the eastern margins of the Atlantic Ocean. Marine Geology 13, 91–106.

Cox, E., Mazurek, M.A., Simonei, B.R.T., 1982. Lipids in Harmattan aerosols in Nigeria. Nature 296, 848–849.

d'Almieda, G.A., 1986. A model for Saharan dust transport. Journal of Climatology and Applied Meteorology 25, 903–916.

Davis, J.C., 1986. Statistics and Data Analysis in Geology. John Wiley & Sons, New York.

Dickson, K.B., Benneh, G., 1995. A New Geography of Ghana, 3rd ed. Longman.

Dionisio, K.L., Arku, R.E., Hughes, A.F., Vallarino, J., Carmichael, H., Spengler, J.D., Agyei-Mensah, S., Ezzati, M., 2010. Air pollution in Accra neighborhoods: spatial, socioeconomic, and temporal patterns. Environmental Science & Technology 44 (7), 2270–2276.

Drees, L.R., Manu, A., Wilding, L.P., 1993. Characteristic of aeolian dust in Niger, West Africa. Geoderma 59, 213–233.

ELTRA, 1995. CS500 Simultaneous Carbon/Sulfur Determinator. ELL TRA GmbH, Neuss.

Engelstaedter, S., Tegen, I., Washington, R., 2006. North African dust emissions and transport. Earth-Science Reviews 79, 73–100.

Goossens, D., Rajot, J.L., 2008. Techniques to measure the dry aeolian deposition of dust in arid and semi-arid landscapes: a comparative study in West Niger. Earth Surface Processes and Landforms 33, 178–195.

Goudie, A.S., Middleton, N.J., 2006. Desert Dust in the Global System. Springer, Berlin, pp. 147–166.

He, C., Breuning-Madsen, H., Awadzi, T.W., 2007. Mineralogy of dust deposited during the Harmattan season in Ghana. Danish Journal of Geography 107 (1), 9–15.

Kalu, A.E., 1979. The African dust plume: its characteristics and propagation across West Africa in winter. In: Morales, C. (Ed.), Saharan Dust: Mobilization, Transport, Deposition. Wiley, New York, pp. 95–118.

Kuo, S., 1996. Phosphorus. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis Part 3. Chemical Methods. Soil Science Society of America and American Society of Agronomy, Madison, USA, pp. 869–919.

Lyngsie, G., Awadzi, T.W., Breuning-Madsen, H., 2011. Origin of Harmattan dust settled in Northern Ghana—long transported or local dust? Geoderma. doi:10.1016/j.geoderma.2011.07.026.

McTainsh, G., 1980. Harmattan dust deposition in northern Nigeria. Nature 286, 587–588.

McTainsh, G., Walker, P.H., 1982. Nature and distribution of Harmattan dust. Zeitschrift für Geomorphologie N.F. 26, 417–435.

McTainsh, G., Nickling, W.G., Lynch, A.W., 1997. Dust deposition and particle size in Mali. Catena 29, 307–322.

Møberg, J.P., Esu, I.E., Malgwi, W.B., 1991. Characteristics and constituent composition of Harmattan dust falling in Northern Nigeria. Geoderma 48, 73–81.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2, Chemical and Mineralogical Properties. ASA and SSSA, Madison, WI, USA, pp. 403–430.

Operators Guide, 1998. Malvern Mastersizer, 2000. Malvern Instruments Ltd., Worchestershire, UK.

Ramsperger, B., Herrmann, L., Stahr, K., 1998. Dust characteristics and source-sinks relations in eastern West Africa (SW Niger and Benin) and South America (Argentinean Pampas). Zeitschrift fur Pflanzenernahrung und Bodenkunde 161, 357–363.

Resch, F., Sunnu, A., Afeti, G., 2008. Sahara dust flux and deposition rate near the Gulf of Guinea. Tellus 60B, 98–105.

Stoorvogel, J.J., van Bremen, N., Janssen, B.H., 1997. The nutrient input by Harmattan dust to forest ecosystem in Côte d'Ivoire, Africa. Biogeochemistry 37, 145–157.

Sunnu, A., Afeti, G., Resch, F., 2008. A long-term experimental study of the Saharan dust presence in West Africa. Atmospheric Research 87, 13–26.

Tiessen, H., Hauffe, H.-K., Mermut, A.R., 1991. Deposition of Harmattan dust and its influence on base saturation of soils in northern Ghana. Geoderma 49, 285–299.