Biogeochemistry **37:** 145–157, 1997.

The nutrient input by Harmattan dust to a forest ecosystem in Côte d'Ivoire, Africa

J. J. STOORVOGEL[1], N. VAN BREEMEN[1] and B. H. JANSSEN[2]
[1] *Dept. of Soil Science and Geology, Agricultural University, P.O. Box 37, 6700 AA Wageningen, The Netherlands;* [2] *Dept. of Soil Science and Plant Nutrition, Agricultural University, P.O. Box 8005, 6700 EC Wageningen, The Netherlands*

Accepted 12 September 1996

Key words: Côte d'Ivoire, dry deposition, dust composition, Harmattan, nutrient balance

Abstract. During December and January, dry northeasterly surface winds (the Harmattan) distribute dust over West Africa. Rate of deposition and some chemical and physical characteristics of Harmattan dust were measured in Taï National Park in the southwest corner of Côte d'Ivoire during the 1990–1991 dry season. The dust deposition was estimated by the classical water-filled basin method and by using canopy drip to account for deposition on tree canopies. Contamination by local biotic debris in both, water-filled basin and canopy drip collectors, was corrected for by using Ti (which appears to be wholly of atmospheric origin) as a reference element. Harmattan dust in Taï consisted mainly of kaolinitic silt finer than that collected in North Nigeria, closer to the source area in the Chad basin. The estimates of seasonal deposition rates were 33 to 47 kg ha^{-1} for the water-filled basin method and around 80 kg ha^{-1} for the canopy drip method. The higher value in canopy drip was in agreement with expected higher deposition of fine dust on the canopies than on a water surface, and was therefore considered more reliable to estimate nutrient inputs by Harmattan dust deposition. The seasonal nutrient input by dust was thus estimated to be 0.11 kg ha^{-1} for P, 2.5 kg ha^{-1} for K, 3.5 kg ha^{-1} for Ca and 0.4 kg ha^{-1} for Mg.

Introduction

Large-scale destruction of the West African equatorial forest has decreased the original 1.1 million km^2 of moist evergreen forest by 87% (FAO/UNEP estimate for 1985 by Martin (1991)). With a surface area of 3,400 km^2, the Taï National Park in the southwestern part of Côte d'Ivoire (Figure 1) is one of the last vast forested areas in the region. Development of sustainable agriculture and silviculture requires knowledge of the nutrient budgets. Apart from biological N fixation, wet and dry deposition are the only natural sources of external nutrient inputs in the area. The objective of this study was to estimate nutrient input into the forest through deposition of Harmattan dust.

The Harmattan aeolian system is receiving increasing attention in relation to the possible desertification of the Sub Saharan Sahel zone and the negative effects of dust entrainment in the Central Chad basin (Rapp 1974; Morales

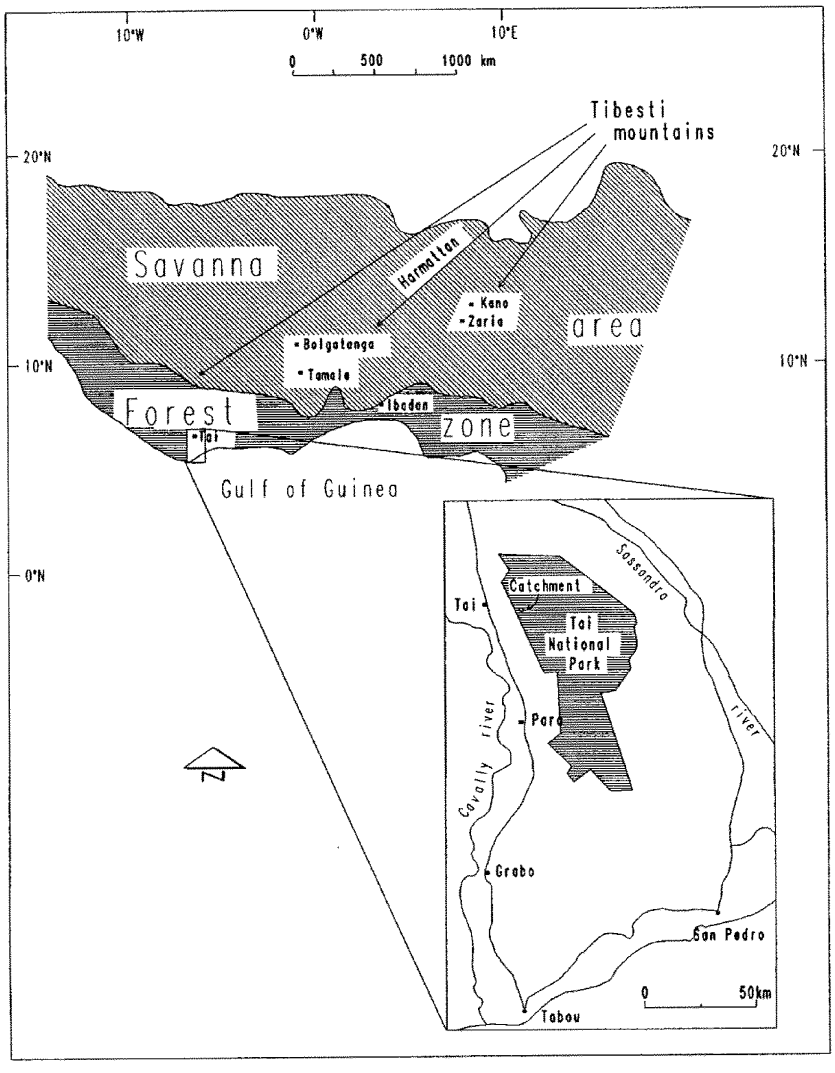

Figure 1. The location of the study area and the Harmattan aeolian system in December-January.

1979; McTainsh 1986). Few authors (e.g. Tiessen et al. 1991; Drees et al. 1993) have considered the role of nutrient inputs by dust in low-fertility soils, despite the fact that the productivity of many ecosystems on these soils is strongly affected by small changes in nutrient availability (Penning de Vries & Djitèye 1982; Janssen et al. 1990; Noij et al. 1993). When the Intertropical Convergence Zone is in its southernmost position, in December and January, the northeastern Monsoon may reach the Equatorial forest zone and dust from

the Chad basin will be transported over West Africa (Pye 1987; Baudet & Bertrand 1988).

In the savanna area, mainly the coarser particles are deposited. In areas deprived of vegetation, secondary entrainment of fine dust takes places (McTainsh 1985). The dust plume is enriched when passing the southern savanna area, where the fallow vegetation is being burned during the Harmattan season (Baudet & Bertrand 1988). The residuary refined and enriched dust will deposit on the Equatorial forest zone, including the Taï area.

The classical method to determine the rate of dust deposition is by the use of a water-filled basin in which the dust particles are collected (McTainsh 1985). However, the structure of a forest canopy differs strongly from a water surface in terms of roughness length. Consequently, dust deposition on a forest canopy is likely to differ from that on a water surface, and the method based on the water-filled basin may be inappropriate to assess dust deposition in forest areas. Therefore, we used the forest canopy itself as the collector, as was done for water-soluble aerosols by Lindberg et al. (1988). Assuming that practically all dust deposited on the canopy is washed by the first rains after the dry season, dust deposition can be measured by collecting and analysing canopy drip (henceforth called "canopy drip method"). To account for contamination by local sources, the composition of the Harmattan dust, including the content of a reference element unique to the Harmattan dust, had to be used in connection with this method. In this paper we present dust input measurements using the water-filled basin method and the canopy drip method during the 1990–1991 Harmattan season. It was part of a larger study of the gross inputs and outputs of nutrients in undisturbed forest of the Taï area (Stoorvogel 1993, Stoorvogel et al. 1997).

Materials and methods

The main study plot was a forest catchment of 117 ha in the western part of Taï National Park at 7°20 N latitude and 5°52 W longitude (Figure 1).

Sampling and analysis of dust particles

Nutrient input by dust is calculated as the product of the concentration of nutrients in the dust particles and the rate of dust deposition. The dust particles for chemical and physical characterisation were sampled directly from the air using a modified version of the Gromoz apparatus (Vrins et al. 1985) (Figure 2). An air pump of 1000 W capacity filtered air through a glass fibre filter (Sleicher & Schuell glass fibre filter No. 10) of low air resistance. Because it is practically impossible to separate the dust particles from the glass fibres

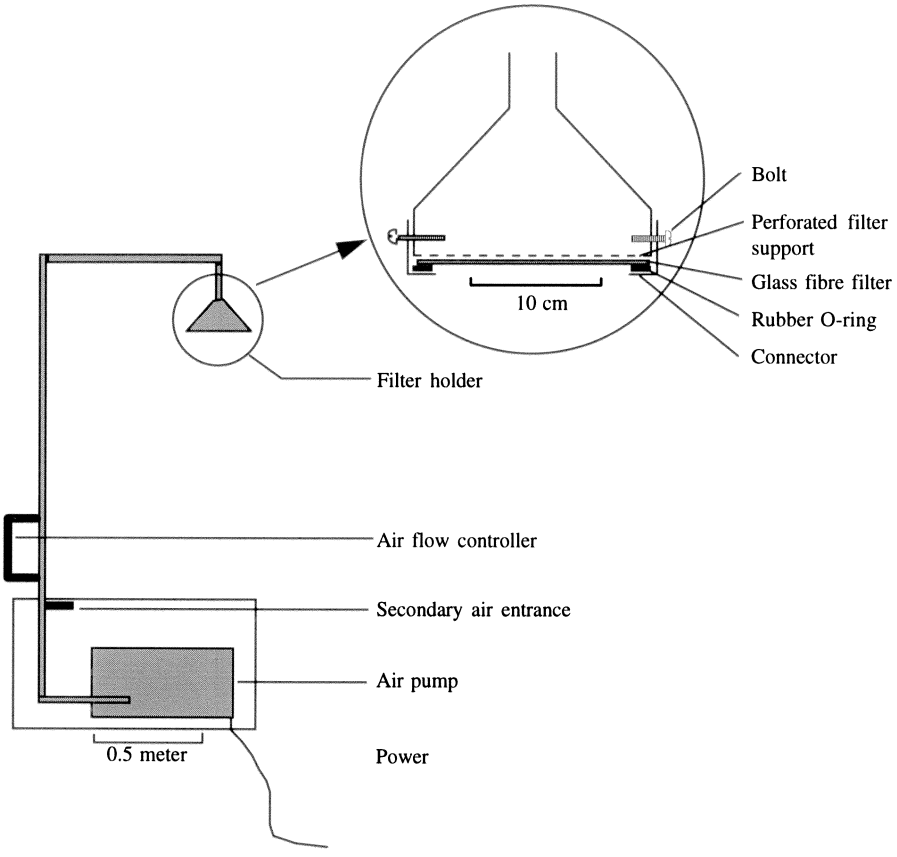

Figure 2. An adapted version of the Gromoz dust sampling apparatus (Vrins et al. 1985).

of these filters, filters with and without dust were analysed for the chemical characterisation of dust. Samples of dust were taken at 2 meters above the ground surface in a 2-ha open field surrounded by primary forest, which was used for meteorological observations. The field was completely covered with a low grass and weed vegetation. The apparatus was installed each sampling day after the morning mist had disappeared (normally around 10 am) and was kept running for 4–8 hours. Sampling took place in the first two weeks of January, 1991, the only period when the concentration of dust was high enough for effective sampling.

Two glass fibre filters with dust were used for particle size assessment by scanning electron microscopy (SEM). A total of 10 micrographs were made at magnifications of 1250, 2500 and 5000 times. On the micrographs, six size classes were distinguished, and per class the numbers of particles were

counted. For the elemental composition, three filters with dust particles were ground for 5 minutes in a Wolfram-Carbid ball mill. Loss on ignition was determined by heating the samples to 600°C, rather than the usual 900°C to avoid melting of the glass fibres. The whole sample was melted with lithium tetraborate to glass disks and subsequently analyzed on a Philips X-ray fluorescence assembly. The system was calibrated using USGS geochemical standards as listed by Abbey (1980). The same procedure was followed for two clean filters to correct for the filter material in the other analysis. As the filter material was included in the analysis, the sample was diluted resulting in a lower accuracy of the XRF analysis. A mineralogical identification of dust was done using X-ray diffraction on one filter. To check whether a bias in the size of dust particles collected on the glass fibre filter could affect the estimate of the chemical composition of the dust, 30 particles of different diameter between 2 and 10 μm were analyzed with a X-ray microanalysis system connected with a scanning electron microscope.

Rate of dust deposition

Water-filled basin method

Six round plastic basins with a diameter of 50 cm and a rim of 10 cm were installed at three different sites. Two basins were placed in the forest canopy at a height of 41 meters, two on the meteorological field, and two in a young coffee plantation, just outside the national park, at a height of 1 m above the coffee plants. The basins were filled with distilled water to a depth of 2–2.5 cm; water was replenished automatically. Leaves and branches that had fallen in the basins were taken out and thoroughly rinsed with demineralized water above the basin to collect any dust from such plant fragments. The basins were installed on 19 December 1990 (well before the Harmattan reached Taï) and maintained until 6 February 1991. Next the basins were emptied, the contents were filtered over a Whatman 542 ashless filter, and the residues were dried and weighed. The quantity of material was so small that residues from the two basins at each site were pooled to one sample. After ignition of the samples at 900°C, the samples were analyzed by XRF using the same procedure as for the glass fibre filters.

Canopy drip method

To collect canopy drip, 56 plastic funnels of 15 cm diameter with collector bottles were placed at an height of 1.5 m above the forest floor every 50 m in 3 transects of approximately 900 m. Canopy drip water was collected from the last two rain showers before the Harmattan season (30 December 1990) and during the first two rain showers after the Harmattan season (13

and 15 February 1991). Rainfall was absent during the Harmattan season. The collectors were maintained during the Harmattan season to include dust deposition directly on the forest floor and dust in dew drip. They were emptied after every rainfall event and rinsed with demineralized water. The contents of the collectors were combined per transect, thus giving three samples per rain event. The canopy drip water was filtered over a Whatman 542 ashless filter and the residues were analysed using XRF, following the same procedures as for the glass fibre filters.

To test the assumption that all the dust particles are washed from the canopy with rainfall, leaves were collected at fifteen positions in the vegetation at heights between 3 and 43 meters. The branches to be sampled were selected to obtain a maximum variation in height and foliage, but were restricted to three spots in the forest where tree climbing was possible. Three leaves from every position were placed between two small glass slides and stored in a container with silica gel for preservation. This was done weekly during the Harmattan season, from 3 January 1991 till 2 February 1991 and after the two rain events in February. One cm^2 sections of each of the 315 leaves were examined for dust particles under the microscope at a magnification of 500.

Correction for contaminations in dust samples

Both, drip water and basin water do not only contain dust but also contaminations from local sources like particulate plant-derived material, insects, animal faeces and dissolved material in rain water. To be able to calculate the fractions of dust and contaminations in the dried residues, a reference element was analysed. Titanium was chosen as a reference because it is strongly lithophilic, and relatively abundant in aeolian dust with a fairly narrow range of mass fractions (0.6–1.4% of TiO_2 in 11 samples from all over the world; Pye 1987). Further it is practically insoluble in water (Hutton 1977). Therefore, the mass fractions of Ti in dry matter of plants and animals are very low: $<10^{-3}$ and $<10^{-4}$ g kg^{-1}, respectively (Bowen 1966; Brooks 1973). Hence Ti is an ideal index element in the particular case that the bulk of contaminants in collectors of aeolian dust consists of organic materials. The Ti method would lead to an overestimation of Harmattan dust inputs if contaminants included local dust and droppings of flying animals that would contain soil material. In particular birds may ingest mineral grains to aid digestion (M.C. Reheis, pers. comm.). To test for such possible contributions of Ti sources other than Harmattan dust, reference samples of canopy drip were collected before the Harmattan season.

Table 1. Particle size distribution (mass fraction in%) of Harmattan dust collected in the Taï region and two regions in North Nigeria (for locations see Figure 1).

	Taï Côte d'Ivoire[1]	Zaria-Kano Nigeria[2]	Zaria Nigeria[3]
Clay (<2μm)	2	24.9	1
Fine silt (2–20 μm)	98	42.2	80
Coarse silt (20–50 μm)	0	14.5	16
Fine sand (50–125 μm)	0	16.6	3
Medium sand (125–250 μm)	0	1.2	0
Coarse sand (250–2000 μm)	0	0.7	0

[1] Based on particle counts, re-calculated to mass fraction.
[2] Möberg et al. 1991.
[3] Whalley & Smith 1981.

Results and discussion

Physical and chemical characteristics of dust

The dust collected on the glass fibre filters consisted almost completely of fine silt (Table 1). Table 1 suggests that the fine silt fraction of dust increases from the centre of the source. The relatively high clay content found in Zaria-Kano (Möberg et al. 1991) may be due to disintegration after sample treatment of coarse silt-sized aggregates consisting of fine silt and clay which were observed in Nigerian Harmattan dust by Whalley and Smith (1981).

The elemental composition of the dust (average value of three samples, Table 2) showed less SiO_2 and more Al_2O_3 than samples from Nigeria (Doyne et al. 1938; McTainsh & Walker 1986; Möberg et al. 1991).

X-ray diffraction revealed a distinct peak at 0.333nm indicating the presence of quartz. In addition, presence of kaolinite was indicated by a d_{001} peak at 0.716 nm and a d_{002} peak at 0.356 nm. No other minerals were found to be present. The X-ray microanalysis gave a composition close to that of kaolinite for 28 of the 30 dust particles, while the other two were dominated by SiO_2 (Stoorvogel 1993).

No systematic change in elemental composition of the aerosols with increasing distance from the source can be found, but the low silica and higher aluminium content in the Taï dust supports that dust becomes relatively enriched in kaolinite as the distance to the source increases (Table 2). As indicated by Pye (1987) and McTainsh (1980) differences in chemical composition may also originate from secondary entrainment of dust.

Table 2. Comparison of the chemical composition (mass fraction of the oxide components in %) of Harmattan dust collected in the Taï region (average of three samples, range between parenthesis) and three regions in Nigeria (for locations see Figure 1).

	Taï Côte d'Ivoire	Ibadan, Nigeria[1]	Kano, Nigeria[2]	Zaria, Kano Nigeria[3]	Kano, Nigeria[4]	Zaria, Nigeria[4]
SiO_2	48 (44–52)	49.34	66.03	55.3	57.19	57.45
Al_2O_3	24 (19–27)	10.34	11.08	21.9	12.11	10.64
CaO	6.1 (5.3–6.6)	5.28	1.13	7.00	3.61	2.88
$Fe_2O_3^5$	1.9 (1.5–2.5)	4.14	4.45	1.72	5.30	4.34
MgO	0.9 (0.8–0.9)	2.07	0.82	0.12	0.81	0.81
K_2O	3.7 (2.4–4.9)	1.62	2.04	1.38	2.95	3.26
Na_2O	0.7 (0.5–0.9)	0.80	0.91	0.06	1.46	2.14
TiO_2	0.3 (0.2–0.3)	0.66	0.73	1.10	0.83	0.82
P_2O_5	0.3 (0.2–0.3)	N.D.	0.17	N.D.	0.24	0.18
MnO	0.1 (0.1–0.1)	N.D.	0.10	0.05	0.08	0.09
LI[6]	11.4 (11.3–13.6)	24.81	12.79	11.1		
Total	97.4 (96.9–98.2)	99.06	100.25	99.73		

[1] Doyne et al. 1938.
[2] McTainsh & Walker 1986.
[3] Möberg et al. 1991.
[4] Wilke et al. 1984.
[5] Fe_2O_3 + FeO expressed as % Fe_2O_3.
[6] Loss of ignition.

Rate of dust deposition

Two basic assumptions were made for the use of Ti as a reference element:

i) All Ti originates from Harmattan dust. This appears to be correct since Ti was detected in canopy drip shortly after, but not before the Harmattan season.

ii) Dust deposited on the canopy and dust collected with the Gromoz apparatus have essentially the same chemical composition. Because (1) X-ray microanalysis showed that dust chemical composition was homogeneous with a narrow range in particle size and (2) the material observed microscopically on the tree leaves had the same particle size range, the assumption appeared justified.

An additional assumption was made for the canopy drip method:

iii) All dust deposited washes down with canopy drip. Figure 3 shows the change in numbers of dust particles on the leave surface during the Harmattan season. With the first two rain showers after the Harmattan season, 96% of all the dust particles present on the leaves were washed off. For this reason, the input estimate was corrected for the remaining 4%.

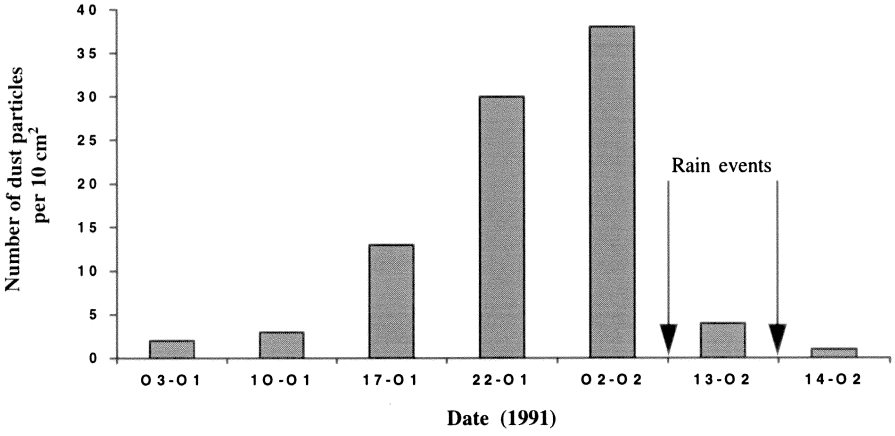

Figure 3. Average number of dust particles per 10 cm^2 leaf surface.

Table 3. Rates of residue deposition, mass fraction of TiO_2 in residues, calculated fractions of contamination in the residue and calculated rates of dust deposition during the 1990–1991 Harmattan.

Sampling method	Residue kg ha^{-1}	TiO_2 g kg^{-1}	Dust kg ha^{-1}
Basin, canopy	89	1.56	46
Basin, cleared field	56	1.77	33
Basin, coffee	95	1.48	47
Canopy drip			
– average	137	1.69	76
– standard deviation	43	0.54	16

The TiO_2 contents in the residues of the water filled basins ranged from 1.48 to 1.77 g kg^{-1}. The TiO_2 content of dust was 3 g kg^{-1}. Because the total mass of material collected in the basins was 56–95 kg ha^{-1}, the amount of dust deposited ranged from 33 (= 56∗1.77/3) at the cleared field to 47 (= 95∗1.48/3) kg ha^{-1} in the coffee field (Table 3). The lower Ti content of the collected residue indicates that the material collected in the basins was highly contaminated with other inputs from local sources.

Residues from canopy drip collected after the Harmattan season had a TiO_2 content of 1.69 g kg^{-1}. The total mass of residues was 137 kg ha^{-1}, equivalent to a dust deposition of 77 (= 137∗1.69/3) kg ha^{-1}. Canopy drip was contaminated with non-Harmattan material to the same degree as residue in the water-filled basin, but the amount of dust collected by the canopy was higher. Correcting for the 4% of the dust particles that were not washed off

the canopy, the total deposition of dust in the 1991 Harmattan season amounts to 80 (= 77∗100/96) kg/ha. Multiplying this value with the nutrient contents presented in Table 2 results in estimates of nutrient inputs through Harmattan dust of 0.11 kg for P, 2.5 kg for K, 3.5 kg for Ca and 0.4 kg for Mg per ha per season.

The dust deposition estimated by the canopy drip method is about twice that in the wet basins. This difference can be explained by the difference in deposition characteristics of the basin and the forest canopy. The much rougher surface of the forest canopy increases the deposition area and allows for turbulent transport of dust into the canopy. Both factors increase dust deposition on a forest over that to a flat surface. For instance, deposition of water-soluble Ca aerosol on temperate forest canopies was increased by about 0.5 ∗ LAI (Leaf Area Index, the ratio of (one-sided) leaf surface area to ground surface; Lindberg et al. 1988). It indicates that the water-filled basin method is not suited to assess dust deposition in a tropical forest area. The relatively small variation among the three transects where canopy drip was collected indicates that the number and the size of the funnels is satisfactory. Nevertheless, the accuracy with which the chemical composition of Harmattan dust was determined is relatively low, due to the dilution of the sample with the filter material. Therefore the canopy drip method should be seen as an approximate estimate of the nutrient input by Harmattan dust, yielding a dust deposition in the approximate range of 60–100 kg/ha.

The significance of nutrient inputs from Harmattan dust can be illustrated by comparison with inputs in wet deposition, and with outputs through creek water, sediments and organic debris (Stoorvogel et al. (1996)). Annual inputs by wet deposition are higher than by dry deposition for K, Ca and Mg, whereas dry deposition of P exceeds the atmospheric input by wet deposition (Table 4). In contrast to wet deposition, nutrient inputs by Harmattan dust takes place with a high rate over a short amount of time (generally less than 1 month). Stream water outputs exceed atmospheric inputs for all nutrients. For K and Ca appreciable portions of the output are compensated for by the Harmattan dust, while Harmattan inputs of P and Mg are relatively small. In contrast to the other inputs and outputs, Harmattan input is characterised by a high rate during a short period of time (approximately three weeks).

The rate of dust deposition, measured with the water-filled basin method, is compared with data from Ghana and Nigeria in Table 5. Although the data originate from different years of observation, the rate of dust deposition apparently decreases with increasing distance from the source of the dust in the Chad basin.

Table 4. Nutrient inputs through Harmattan dust compared with nutrient input through wet deposition, and with nutrient outputs through creek water, sediments and organic debris in the Taï region. All values are in kg $ha^{-1}yr^{-1}$.

	P	K	Ca	Mg
Harmattan	0.11	2.5	3.5	0.4
Wet deposition	0.02	3.5	6.5	0.9
Nutrient outputs	1.56	18.7	25.3	9.4
Harmattan/outputs (%, rounded)	7	13	14	4

Table 5. Dust deposition, measured with the water-filled basin method, for different sites in West Africa in relation to the distance between collection site and the source area in the Chad basin (for locations see Figure 1).

Location	Distance (km)	Dust deposition (kg $ha^{-1}yr^{-1}$)	Reference	Years of observation
Taï area	2700	42[1]	This study	1990–1991
Taï area	2700	80[2]	This study	1990–1991
Bolgatanga-Tamala, Ghana	2000	150[2]	Tiessen et al. 1991	1987–1989
Kano, Nigeria	1000	850[2]	Möberg et al. 1991	1984–1985
Kano, Nigeria	1000	991[2]	McTainsh 1980	1978–1979

[1] Measured using Ti as an index.
[2] Measured as total residue.

Conclusions

The traditional water-filled basin collectors underestimate rates of deposition of Harmattan dust on tropical rain forest by at least 50%, because they are less efficient than tree canopies in trapping atmospheric dust. This difference is in agreement with expected differences in deposition characteristics of dust on water surface and tree canopy. Practically all of the dust deposited on leaf surfaces is washed off by rain. A reference element that occurs almost uniquely in the atmospheric dust source is needed to account for contamination from local sources in both water-filled basins and in canopy drip collectors. In the studied area Ti appeared to be suitable for that purpose.

Harmattan dust input to the Taï forest was about 80 kg ha^{-1} during the dry season 1990–1991, and acted as a significant source of nutrients K and Ca.

Acknowledgement

The present study was made possible by a grant of the Tropenbos Foundation, which is aimed at generating knowledge for better conservation and sustainable use of tropical rain forest.

References

Abbey S (1980) Studies in 'Standard samples' for use in the general analysis of silicate rocks and minerals. Part 6: 1979 edition of 'usable' values, Geol. Surv. Canada Pap. 80–14

Baudet GJR & Bertrand JJ (1988) Circulation atmosphérique, composition et propriétés physico-chimiques de l'aérosol de Côte d'Ivoire. In: Lamotte M & Tireford JL (Eds). Le climat de la savane de Lamto (Côte d'Ivoire) et sa place dans les climats de l'Ouest africain. Trav. cherch. Lamto (RCI) 8: 117–146

Bowen HJM (1966) Trace elements in biochemistry. Academic press, New York

Brooks RR (1973) Biogeochemical parameters and their significance for mineral exploration. J. Appl. Ecol. 10: 825–836

Doyne HC, Hartley KT & Watson WA (1938) Soil type and manurial experiments in Nigeria. In: Proceedings of the Third West African Agricultural Conference, Vol 3 (1): 227–298

Drees LR, Manu A & Wilding LP (1993) Characteristics of aeolian dust in Niger, West Africa. Geoderma 59: 213–233

Hutton JT (1977) Titanium and zirconium minerals. In: Minerals in soil environments (pp. 673–688). Soil Science Society of America, Maddison (WI)

Janssen BH, Noij IGAM, Wesselink LG & Van Grinsven JJM (1990) Simulation of the dynamics of nutrients and moisture in tropical ecosystems. Fert. Res. 26: 145–156

Lindberg SE, Lovett GM, Schaefer DA & Bredemeijer M (1988) Dry deposition velocities and surface-to-canopy scaling factors for aerosol calcium from forest canopy throughfall. J. Aerosol Sci. 19: 1187–1190

Martin C (1991) The rain forests of West Africa: ecology – threats – conservation. Birkhauser Verlag, Basel

McTainsh G (1980) Harmattan dust deposition in northern Nigeria. Nature 286: 587–588

McTainsh GH (1985) The nature and origin of the aeolian mantles of central northern Nigeria. Geoderma 33: 13–37

McTainsh GH (1986) A dust monitoring programme for desertification control in West Africa. Environmental Conservation 13: 17–25

McTainsh GH & Walker PH (1986) Nature and distribution of Harmattan dust. Z. Geomorph. N.F. 26(4): 417–435

Möberg JP, Esu IE & Malgwi WB (1991) Characteristics and constituent composition of Harmattan dust falling in Northern Nigeria. Geoderma 48: 73–81

Morales C (1979) Saharan dust. Mobilization, transport, deposition. Papers and recommendations from a workshop held in Gothenburg, Sweden, 25–28 April 1977. Scope 14. John Wiley, Chichester

Noij IGAM, Janssen BH, Wesselink LG & van Grinsven JJM (1993) Modelling nutrient and moisture cycling in tropical forests. Tropenbos Series 4. The Tropenbos foundation, Wageningen

Penning de Vries FWT & Djitèye MA (Eds) (1982) La productivité des pâturages sahéliens. Une étude des sols, des végetations et de l'exploitation de cette resource naturelle. Centre for Agricultural Publishing and Documentation

Pye K (1987) Aeolian dust and dust deposits. Academic Press, London

Rapp A (1974) A review of desertization in Africa. Water, vegetation and Man. Secr. Int. Ecology, Rep. Stockholm

Stoorvogel JJ (1993) Gross inputs and outputs of nutrients in a forest ecosystem, Taï area, Côte d'Ivoire. Tropenbos Series 5. The Tropenbos foundation, Wageningen

Stoorvogel JJ, Janssen BH & Van Breemen N (1997) The nutrient budgets of a forested watershed and its proper forest ecosystem in the Taï National Park in Côte d'Ivoire. Biogeochem. 37: 159–172

Tiessen H, Hauffe H-K & Mermut AR (1991) Deposition of Harmattan dust and its influence on base saturation of soils in Northern Ghana. Geoderma 49: 285–299

Vrins ELM, Hofschreuder P, ter Kuile WM, Oeseburg F & Alderliesten PT (1985) Het vangstrendement voor grof stof van de mens en van meetinstrumenten in de buitenlucht. Vakgroep Luchthygiëne en-verontreiniging. Landbouwhogeschool Wageningen

Whalley WB & Smith BJ (1981) Mineral content of Harmattan dust from northern Nigeria examined by scanning electron microscopy. J. of Arid Env. 4: 21–29

Wilke BM, Duke BJ & Jimoh WLO (1984) Mineralogy and chemistry of Harmattan dust in northern Nigeria. Catena 11: 91–96