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Bypass flow and leaching of nitrogen in a Kenyan Vertisol at the onset of the growing season

E. M. A. Smaling[1] & J. Bouma[2]

Abstract. Bypass flow and concurrent leaching of nitrogen were studied on a Vertisol in south-western Kenya under rangeland and bare, manually tilled cropland. Showers of 30 mm/hr were simulated, causing bypass flow of 47–62% in rangeland topsoils and 19–49% in cropland topsoils. Volumetric water contents after experimentation increased from 28 to 35% and from 24 to 38%, respectively, for the two land-use types.

In rangeland samples up to 3.4 kg N/ha was found in the leachate of unfertilized soil. With a fertilizer application of 50 kg N/ha, up to 5.7 kg N/ha was lost from a pre-wetted soil, and more than 20 kg N/ha from dry soil. In cropland topsoils up to 2.2 kg N/ha was lost from unfertilized soil, and only up to 2.9 kg N/ha from both dry and prewetted fertilized soil. Although Vertisols are often linked with excess water, the phenomenon of bypass flow can cause water stress to crops in their early growth stages. Nitrogen leaching losses were large from dry grassland, but prewetting helped to decrease them. On intensively cultivated cropland there was little nitrogen leaching; the tilled topsoil was able to retain most of the supplied nitrogen.

INTRODUCTION

The availability of water plays a pivotal role in the evaluation of land for agricultural purposes. It can be determined by calculating the fluxes of water which enter and leave the rooted volume of soil (Bouma, 1984). In soils with continuous macropores, such as cracking clays, water availability is a dynamic land quality. Swelling and shrinking alternate through the seasons, causing constantly changing pore size distributions and pore-continuity patterns (White, 1985; Bouma & Loveday, 1988; Bronswijk & Evers-Vermeer, 1990). At the onset of the growing season, when soils are relatively dry, rainwater partly infiltrates along the vertically continuous cracks and macropores. As this water bypasses an unsaturated soil matrix, the process has become known as 'bypass flow' or 'short-circuiting' (Bouma *et al.*, 1981). Figure 1 shows a schematic representation of the different types of water flow in the root zone of a dry, cracked clay.

As a result of a build-up of inorganic nitrogen during the preceding dry months and a flush of nitrogen mineralization in the topsoil at the start of the rains, the bypassing water contains soil-derived nitrogen (Birch, 1958; Sanchez, 1976); mineralized nitrogen must first diffuse from within the aggregates towards the larger channels (Wild, 1972). Fertilizer nitrogen applied at planting may be leached quickly when washed into draining macropores. When fertilizer is applied as a topdressing several weeks after

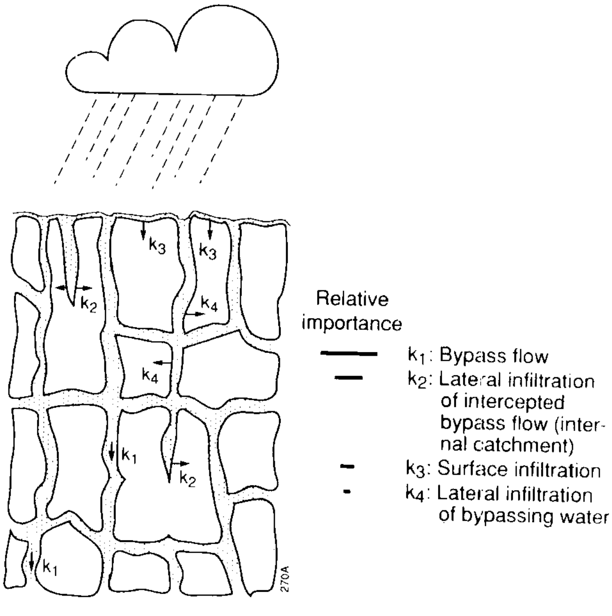

Fig 1. Schematic representation of water flow in the root zone of a dry, cracked clay. k_1: bypass flow, leaving the root zone, k_2: lateral infiltration from bypass flow, caught inside discontinuous cracks within the root zone (internal catchment), k_3: surface infiltration into aggregates, k_4: lateral infiltration of bypassing water that is in contact with the pore walls.

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[1] DLO The Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), PO Box 125, 6700 AC Wageningen, The Netherlands.

[2] Wageningen Agricultural University, Department of Soil Science and Geology, PO Box 37, 6700 AA Wageningen, The Netherlands.

planting, the chances of nitrogen being intercepted by the crop are greater as roots have started to develop.

Bypass flow and concurrent nitrogen fertilizer leaching were studied in Dutch pastures on cracking, riverine Fluvisols (Bouma *et al.*, 1981; Dekker & Bouma, 1984). These processes have hardly been studied in tropical environments, although there are large areas of cracking clays, mostly classified as Vertisols (IBSRAM, 1989). In Kenya, there are 2.8 million hectares of Vertisols in areas that range from marginally to very productive, with average annual rainfall of 500–1200 mm; on these soils there are good crop responses to fertilizer nitrogen (Ikitoo, 1989).

This paper describes the amount and spatial variability of bypass flow and leaching of nitrogen in a Kenyan Vertisol at the onset of the major rainy season. It is part of an attempt to formulate fertilizer recommendations for annual crops in Kenya that are based on agro-ecological concepts (Smaling & Van de Weg, 1990).

MATERIALS AND METHODS

Study area

The study area was one hectare of flat land near Rodi Kopany, south-western Kenya (0°35′S, 34°30′E). The soils are developed on Tertiary alkali basalts (Wielemaker & Boxem, 1982); the 0–20 cm layer has 54% clay, 2.4% organic carbon, and a pH of 6.2. Between 20 and 50 cm depth, the clay content is 67%. Rotten basaltic rock predominates below a depth of 70 cm. Groundwater was absent within 100 cm. The soils are classified as Eutric Vertisols (Food and Agriculture Organization, 1988) or Typic Pelluderts (Soil Survey Staff, 1975). The rainfall distribution pattern is bimodal with, in 20 out of 30 years, 820 mm between early March and late July and 550 mm between late August and early January. Experiments were conducted in rangeland under perennial grasses and in the adjacent bare cropland manually tilled to a depth of 10–15 cm. Fifteen profiles were sampled: three in rangeland and 12 in cropland. At the end of the growing season, it was observed that the roots of maize in the cropland did not reach deeper than 40 cm. The roots of the perennial grasses, however, followed ped surfaces to 60 cm and below.

Soil morphology

The soils of the rangeland had a strong, angular blocky structure in the topsoil with thin continuous cracks, the aggregates tightly kept together by coarse roots, typical of tropical perennial grasses. The subsoil had coarse prisms, 8–15 cm wide, separated by vertical cracks 0.5–2 cm wide. In the cropland topsoils intensive tillage destroyed macropores but increased total porosity. Below the depth of tillage, the soil had a coarse prismatic structure with slickensides. Vertical cracks were 0.5–1.5 cm wide and continuous to a depth of 60–80 cm.

Bypass flow

Experiments were in late February, at the onset of the rainy season. Showers of 20 and 30 mm were simulated at intensities of 20 and 30 mm/hr. Daily rainfall totals at the site revealed that the applied amounts were exceeded 8–20 times (20 mm) and 4–8 times (30 mm) in the period 1987–89. The intensities were chosen after consulting the Rainfall Frequency Atlas of Kenya, which shows an hourly rainfall intensity in the area of 55–65 mm/hr once in 5 years. In total, there were four groups of samples (Table 1, Part I): (A) 12 rangeland topsoils, receiving 30 mm on day 1, and

Table 1. Summary of experimental data on bypass flow and nitrogen leaching

		I Water application at Day no.			II Bypass flow upon application				III Water content		IV Water content (vol%) at pressure head		V Nitrogen leaching‡ (kg/ha)		
					1		2		before appl. 1	after appl. 2					
Sample	*n*†	1	2	3	mm	%	mm	%	(vol%)	(vol%)	−100 cm	−500 cm	N_0	N_1	N_2
A*	12	30	—	30	14.2 ±5.3	47	18.6 ±2.1	62	28	35	n/d	n/d	1.4–3.4	21–60	1.9–5.7
B	24	30	—	30	5.7 ±2.4	19	14.6 ±2.4	49	24	38	n/d	n/d	1.6–2.2	1.3–1.8§	1.6–2.9
C	16	20	20	—	1.5 ±1.6	7	8.7 ±2.6	44	22	35	68	38	0.8–1.0§	0.9–1.6§	n/d
D	8	20	20	—	11.2 ±1.8	56	14.4 ±1.0	72	38	43	55	51	n/d	n/d	n/d

*A = rangeland, topsoil; B = cropland, topsoil; C = cropland, topsoil; D = cropland, subsoil.
†*n* = number of cylinders tested.
‡N_0 = no fertilizer applied.
N_1 = 50 kg N/ha applied immediately **before** first water application.
N_2 = 50 kg N/ha applied immediately **after** first water application.
§Leaching load found at low bypass flow (< 10 mm); other values at bypass flow of 10–20 mm; n/d = not determined.

again 30 mm on day 3, (B) 24 cropland topsoils, treated like A, (C) 16 cropland topsoils, receiving 20 mm on day 1, and again 20 mm on day 2, (D) eight cropland subsoils, treated like C.

Bypass flow was measured largely according to the field technique of Bouma *et al.* (1981). Four undisturbed samples were excavated from each profile and placed side by side (Fig. 2). PVC cylinders, 25 cm long and 20 cm in diameter, were used. They were sharpened at the bottom and greased prior to sampling to avoid edge-flow along the walls. This method was shown to be effective by checking the fate of a staining agent applied during experimentation. The recent method of Cameron *et al.* (1990), who successfully prevented edge-flow with a watertight seal between soil and casing, however, deserves future consideration. In the filled cylinder, the original soil surface was approximately 5 cm below the upper rim. Grass in the rangeland samples was left in place.

Fig. 2. Excavated soil columns (4 replicates) ready for testing.

Water was gently sprinkled from a measuring cylinder through a fine-meshed sieve held approximately 25 cm above the cylinders. Every 5 min one full minute was spent applying 1/12 of the total volume. The water leaving the base of the column was led through a funnel into measuring flasks, and was recorded every 5 min. Between the showers on Day 1 and Days 2 or 3, the cylinders were left to evapotranspire. The area has a potential evaporation in February of 6 mm/day (Jaetzold & Schmidt, 1982). The mass of the soil-filled cylinder was determined before and after experimentation. The oven-dry mass was measured at the end, allowing calculation of bulk density and volumetric water content. Also, on samples C and D, water content at pressure heads of −100 and −500 cm was determined. Methyl red was applied as a staining agent to the columns to allow recognition of water-conducting macropores (Bouma & Dekker, 1978).

Nitrogen leaching

Of the 60 cylinders, 32 received no fertilizer (N_0). Sixteen cylinders received the equivalent of 50 kg N/ha, applied as calcium ammonium nitrate, just **before** the first shower (N_1). Twelve cylinders received 50 kg N/ha just **after** the first shower and were sprinkled again on day 2 or 3 (N_2). Treatment N_1 implied immediate subjection of the fertilizer to leaching, whereas N_2 allowed the fertilizer to be adsorbed on soil particles or taken up by grass roots prior to the second shower. As different forms of nitrogen may have been displaced, the leachate was analysed for total nitrogen by a semi-micro Kjeldahl procedure (Bremner & Mulvaney, 1982).

RESULTS

Physical measurements

Table 1 (Part II) shows that, on applying 30 mm, bypass flow in rangeland topsoils (A) was 14.2 mm on Day 1 and 18.6 mm on Day 3. The same amount applied to cropland topsoils (B) gave bypass flow of 5.7 mm on Day 1 and 14.6 mm on Day 3. Cropland topsoils receiving 20 mm (C) yielded 1.5 mm of bypass flow on Day 1 and 8.7 mm on Day 2. Cropland subsoils receiving 20 mm (D) had 11.2 mm on Day 1 followed by 14.4 mm on Day 2.

Volumetric water content of the topsoils at the start of the experiment was 28% (rangeland) and 22–24% (cropland), whereas the final water content was 35% (rangeland) and 35–38% (cropland). In the subsoils these values were 38% before and 43% after experimentation (Table 1, Part III). According to conventional flow theory, water can only leave the columns after saturation has been reached at the base of the column. The top of the column should then have a pressure head of −20 cm. When comparing Parts III and IV of Table 1, however, it seems that the volumetric water contents after experimentation still fall short of those corresponding to a pressure head of −500 cm. Anisotropy of the cracking clays was also indicated by the staining test, showing a marked decrease from 60% red surface at a soil depth of 20 cm to about 20% red surface at a depth of 40 cm. At this depth, one or two continuous macropores were entirely responsible for the drainage in the cylinder.

Nitrogen leaching

Table 1 (Part V) shows how much nitrogen was leached. In the rangeland samples (A) up to 3.4 kg N/ha was lost from unfertilized soil (N_0), and up to 5.7 kg N/ha from fertilized, moist soil (N_2). From dry soil (N_1), however, not less than 21–60 kg N/ha was lost.

Losses from the cropland samples were very different, and differences between treatments were small: up to 2.2 kg N/ha from unfertilized soil, up to 1.8 kg N/ha after treatment N_1 (bypass flow < 10 mm) and up to 2.8 kg/ha after treatment N_2 (bypass flow 10–20 mm). As bypass flow in the C-samples was small (< 8 mm), there was also little N leaching: up to 1 kg N/ha in unfertilized plots, and up to 1.5 kg N/ha after treatment N_1.

DISCUSSION AND CONCLUSIONS

In The Netherlands, Bouma *et al.* (1981) recorded 36–47% bypass flow for dry clay soils under grass at input rates of 17–25 mm/hr. They measured final water contents of 30–40% by volume, whereas saturation coincided with 46%. Dekker & Bouma (1984) found final water contents of 38–50%, whereas saturation was reached only at 55%. In the present study, we found 47% bypass flow at an application rate of 30 mm/hr in dry Vertisols under grass. On the final water content, conclusions were similar to those of the studies in The Netherlands, namely that water left the columns long before the soil was saturated.

In the Vertisols, tillage largely disrupted crack continuity in the topsoils. Consequently bypass flow in the tilled topsoils (samples B) was much less than in the rangeland topsoils receiving the same amount of water (samples A), particularly during the first application. This was partly because of the greater initial water content of the rangeland samples, attributable to their strong coarse structure, with water tightly bound inside aggregates; however, water content after experimentation was less in these samples as the total pore volume in the cropland topsoils had been increased by tillage.

Cropland subsoils (samples D) allowed more bypass flow than corresponding topsoils (samples C), again indicating less absorption and a larger macropore continuity in the absence of tillage. Also the subsoils have a larger clay content, less organic matter and less biological activity than topsoils. The effect on bypass flow is evident when comparing the subsoil samples (D) with the non-tilled rangeland topsoils (A), which received larger amounts of water but showed less bypass flow.

Total bypass flow was not only greater in non-tilled samples A and D than in the tilled samples B and C, but also started earlier – 5–8 minutes after application as opposed to 35–45 min after application on Day 1, and 21–27 min after application on Days 2 and 3 in the tilled samples. Man-induced spatial variability can be detected from the standard deviations during the second applications, which are less for the non-tilled samples (7–11%) than for the tilled samples (16–30%). Manual tillage seems to have given each sample some 'random' pore size distribution, resulting in different responses even to the second water application.

Comparison of the tilled topsoils that received different amounts and rates of water (samples B and C) shows that bypass flow increased with increasing water application. Moreover, bypass flow during the second shower was greater in all samples than during the first shower. It apparently increased at greater water contents of the soil as long as cracks were vertically continuous, which is in agreement with Bouma & Loveday (1988).

The large leaching losses of nitrogen (more than 20 kg N/ha) found on dry grassland and the fact that prewetting helped to decrease these losses (up to 6 kg N/ha) agree with earlier findings (Dekker & Bouma, 1984). Apparently, cracks in between the dry strong, coarse aggregates were wide enough to prevent fertilizer from even partly diffusing into the soil. However, intensive tillage, twice prior to planting and once after harvesting to plough in crop residues, decreased nitrogen leaching from a freshly fertilized Vertisol to less than 3 kg N/ha. The tilled topsoil seems able to retain the supplied nitrogen, probably in the smaller and discontinuous pores and through surface infiltration of rapidly dissolving nitrogen (mechanisms k_2 and k_3 in Fig. 1).

This study shows that simple field techniques can enhance our understanding of water availability and nitrogen displacement in Vertisols used as rangeland and as cropland around planting time. Much of the rain water percolates as bypass flow and is thus not available to emerging crops and poorly available to grasses. However, losses of soil- and fertilizer-derived nitrogen are modest as long as the topsoil is carefully tilled. For the farmer and the ecosystem, this is good news, but the researcher waits for the rains to increase and the Vertisol to start swelling, because the next possible loss mechanism, i.e. denitrification, may be just around the corner.

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BOOK REVIEWS

Erosion, Transport and Deposition Processes
Edited by D.E. Walling, A. Yair and S. Berkowicz. International Association of Hydrological Sciences Publication 189. Published by IAHS Press, Wallingford, 1990. 203 pp. US$40, paperback.

This publication selects 13 papers from presentations made at the International Workshop on Erosion, Transport and Deposition Processes with particular reference to semi-arid and arid areas, which was held in Jerusalem – Beer Sheba – Elat in March–April, 1987. The Workshop was organized jointly by the Commission on Measurement, Theory and Application in Geomorphology (COMTAG) of the International Geographical Union and the International Commission on Continental Erosion (ICCE) of the International Association of Hydrological Sciences.

This interaction and overlap between the disciplines of geomorphology and hydrology is reflected in many of the papers, which attempt to answer the charge that the present advances in computer simulation of erosion and depositional processes have gone ahead at such a rate that they have lost 'much of the necessary basis demonstrable by field relationships' (Preface by Schick & Walling). Some concentrate on the understanding of runoff hydrology and hydraulics in semi-arid and arid areas, and state that conventional hydrologic and hydraulic relationships do not apply to desert hillslopes, because of the irregular character of desert ground surfaces, the composite nature of flow processes on desert hillslopes and the spatial and temporal variability of overland flow. Such variations make field observations problematic, so laboratory simulation may be a solution. This approach is used in one paper to determine empirical relationships for the transport capacity of overland flow. The ability of flow to transport eroded material is presented at other scales by various authors in terms of sediment delivery ratio (as related to channel network order) and in terms of the ability of rill flow to evacuate rock fragments of up to 9 cm in diameter.

Another theme in the book is the development and evolution of erosional features. A number of papers discuss the dynamics of gully development, either as related to a steady seepage of irrigation water or in terms of modelling the bifurcation phenomenon associated with gully head development or by field measurements of the processes and rates of gully head recession.

The methodology of geomorphological and hydrological research applicable to semi-arid and arid areas is covered by a comprehensive review of sedimentation studies, outlining the techniques currently used, the possible sources of error and the problems associated with predicting erosion rates from sediment records. Other techniques discussed are the use of a magnetic tracer to measure bed load and of ^{137}Cs to measure erosion, transport and deposition. Walling and Bradley use excellent case studies to demonstrate the value of the ^{137}Cs technique for fingerprinting suspended sediment sources, investigating patterns of soil erosion and sediment delivery, and for elucidating rates and patterns of flood plain deposition.

Many of the papers selected have applications far beyond the climatic confines of semi-arid or arid areas. The field data presented show that experimental work is still alive and well and is being used to develop and validate models of erosion and deposition. These results are essential for better scientific understanding as well as for developing strategies to manage and protect these often fragile environments. This volume succeeds in progressing towards both these objectives.

R. J. Rickson

Statistical Methods in Soil and Land Resource Survey.
By R. Webster and M.A. Oliver. Published by Oxford University Press, Oxford, 1990, 316 pp. £20 paperback (£40 hardback) (ISBN 0-19-823316-7 paperback; 0-19-823317-5 hardback)

For many readers, mention of statistical methods in soil research will call to mind data analyses culminating in