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Earthworm surface casts affect soil erosion by runoff water and phosphorus transfer in a temperate maize crop

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Summary

To test the hypothesis that earthworm surface casts contribute to soil erosion and nutrient transfers in a temperate maize crop, two rainfall experiments were set up. One was focused on the erodibility of earthworm casts, the second examined in how casts affect water runoff and nutrient transfers. Casts produced from anecic and endogeic earthworm species were both analyzed. Visual observations in the field showed no cast transport but only cast disintegration and transfers of particles. Erodibility of newly deposited casts was high and differed significantly between age groups. Cast erosion was significantly positively related to initial mass when young but not when old. The paradox is that despite a high cast abundance (25% of the area) and obvious cast erosion, amounts of sediment and nutrient losses (C, N and P) in the runoff were at least twice as high without, than in the presence of, surface casts. Earthworm activities were shown to act as a physical brake for soil erosion by (i) creating a surface roughness with the deposition of surface casts and (ii) reducing water runoff by associated enhanced water percolation. Once the breaking-down point of the physical resistance of casts was reached, all surface casts were quickly disintegrated and finally completely washed away. The amount of particulate phosphorus recovered in water runoff was 34.7 mg P m^{-2}, while 128.5 mg P m^{-2} was estimated to have been released from casts. The transfers were found to occur over a short-distance through successive deposition/suspension of soil particles in the water runoff.

Key words: Earthworm, surface casts, simulated rainfall, soil erosion, phosphorus

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Introduction

Erosion and runoff from cropland degrade soil quality and fertility, thereby reducing the productivity of the land. When soil is eroded, basic plant nutrients such as nitrogen, potassium or phosphorus are lost. Interest in the dynamics of phosphorus and its release in the environment is due to the implication of this element in the eutrophication of continental waters (rivers, lakes, etc.). Sharpley et al. (1998) proposed remedial measures to control P export including management of sources (fertilizer and manure application) and transport (reduce surface runoff and erosion). In particular, bioavailable forms of phosphorus, comprising P in dissolved and particulate forms, is mostly involved in surface water eutrophication (Sharpley 1993). While many studies have focused on particulate soil erosion, less attention has been directed towards the contribution of earthworm surface casts to soil erosion despite their enrichment in P (Graff 1970; Sharpley & Syers 1976) compared with uningested soil. Sharpley & Syers (1976, 1977) and Sharpley et al. (1979) reported the potential role of earthworm casts for the phosphorus enrichment of runoff waters under permanent pasture in New-Zealand. Previous research in a temperate maize crop has indicated that earthworms might play a role in soil erosion, especially from compacted soils where both the casting activity and the water runoff volumes are the highest (Le Bayon & Binet 1999). In the present study, we tested the hypothesis that earthworm surface casts contribute to soil erosion and nutrient transfers, especially phosphorus, in a temperate maize crop. Two rainfall experiments were set up. One was focused on the erodibility of earthworm casts and its variation among the functional groups of worms and during the ageing processes. The second experiment examined the extent to which deposition of earthworm casts affects both water runoff and nutrient transfers.

Materials and Methods

Experimental site

The study was established under a temperate climate (mild temperatures, high annual rainfall of 750 mm y^{-1}) on a cultivated plot located near Rennes (Brittany, NW France). The field site has a gentle slope of 4.5% and had been under maize with rows of plants running downslope. The soil contents silt (70%) and clay (15%), and low amounts of organic matter (1.8%). The soil pH is 6.4. Observations and measurements were made in spring 1998. At this time, the crop had been harvested in the previous autumn (maize ensilage) and the soil was bare. The site supports an earthworm community of 275 individuals m^{-2}, corresponding to a biomass of 100 g m^{-2}. The endogeic *Aporrectodea caliginosa* and the anecic *Lumbricus terrestris* are the two dominant species (Binet & Le Bayon 1999). Two types of casts were visually distinguished (Le Bayon & Binet 1999): the larger ones produced by the anecic species (AN), and the others by the endogeic species or small anecic worms (ESA). The mean weight of both AN casts and ESA casts had been determined on 100 casts that were randomly collected in the field and dried at 105 °C (AN casts: 1.00 ± 0.23 g and ESA casts: 0.28 ± 0.07 g). In both experiments, an oscillating nozzle type simulator was used for the rainfall simulation. A tent to minimize heterogeneity in rainfall due to wind surrounded the defined plots. The sweeps were of 3 s and the delay time between them was of 2 s 30. The target area was, therefore, not under continuous rainfall. Over the study period, no natural rainfall occurred.

Experiment 1

Two weeks before the simulated rainfall experiment, a "cast production" plot was defined and cleared of casts. Then, daily observations of the surface cast production for 15 days were made to determine exactly the age of each cast present. On the day of the rainfall experiment, three hours before the rainfall started, a total of 60 surface casts of each type were picked up and divided into two morphological age groups as described earlier by Binet & Le Bayon (1999): i) young and fresh ones, *i.e.* the age group of 0–5 d old with a moisture content of 17.8 % (± 0.2) and 17.9% (± 0.1) for AN and ESA casts, respectively, and ii) old and dry ones, *i.e.* the age-group of 10–15 d old with a moisture content of 5.3% (± 0.1) and 4.8% (± 0.05) for AN and ESA casts, respectively. To prevent damage from handling, casts were put on small pieces (4 x 4 cm) of nylon mesh (2 mm). Then, the casts were weighed and measured with a caliper square for their maximal length (a, in cm), width (b, in cm) and height (h, in cm). The ratio b/a varied from 0.65 to 0.75 (± 0.03), indicating an elliptic shape of the casts. So, for each of them, the area in contact with the soil matrix S (in cm^2) was established following the ellipse equation: $S = \frac{1}{2} (\pi ab)$. The volume V (in cm^3) was then calculated from the equation: $V = 1/3\ (Sh)$. All these measurements were made before and after the rainfall simulation. Initial S values were 5.79 ± 0.65 *vs* 4.88 ± 0.46 and V values 3.74 ± 0.59 *vs* 3.08 ± 0.39 for young and old AN casts, respectively. For ESA casts, initial S and V were 3.01 ± 0.39 *vs* 2.32 ± 0.30 and 0.99 ± 0.21 *vs* 1.02 ± 0.19 for young and old casts, respectively. Cast erosion was assessed by ΔS and ΔV calculation. A rainfall plot of 4 m in length x 0.75 m in width was chosen, smoothed and cleared with a road roller (soil bulk density of 1.54 g cm^{-3} ± 0.02 at 5 cm depth), so all the area showed an homogeneous microtopography. Then, the pieces of nylon mesh with each type of cast were randomly placed side by side one centimeter apart on a soil surface of 1.5 m^2. The artificial cast abundance on the rainfall plot was 80 m^{-2}, representing a total mass of 221.9 g m^{-2} (49.7 g m^{-2} and 172.2 g m^{-2} for ESA and AN casts, respectively). The simulated rainfall was of 25 mm h^{-1} for 20 min to reproduce a natural soft rainfall commonly observed during spring (Binet & Le Bayon 1999). Every five minutes, the rainfall was stopped in order to count eroded casts (fuzzy aspect) or disintegrated ones (absence). Because homogeneity of variance from our set of data was not obtained, the erosion of casts related to their age or ecological group was statistically analyzed using the non parametric test of Kruskal-Wallis (Minitab version 12 software). Mann-Whitney test (Minitab version 12 software) was also used to compare the bulk density of casts according to their type.

Experiment 2

Two experimental plots of 4 m length x 0.75 m width (which corresponds to the width of the maize inter-row), separated by 0.75 m from each other, were used. One of them was designed as the control (without surface casts) and the other for determination of cast erosion. All the organic residues (ensilage remains, maize leaves) and all earthworm casts present at the soil surface of the two plots were removed. Then, on the plot designed for assessment of cast erosion, cast production was monitored at 3-day intervals for 15 days before performing the simulated rainfall experiment to locate casts, and record their type and age (details are given in Binet & Le Bayon 1999). Prior to simulated rainfall events, all surface casts produced during the 15 days before were recorded for the erosion plot, while they were removed from the plot designed as the control. The corresponding burrow holes were then hand-closed to minimize their role in infiltration, and so to simulate as far as possible a natural control area without any worm activity.

Two rainfall intensities were used ($I_1 = 37$ mm h^{-1} for one hour and $I_2 = 50$ mm h^{-1} for 30 min), simulating an usual rainstorm under our temperate climate, followed by a less frequent intensity of rainstorm event. Facing each of the two erosion plots, water collectors were installed as described by Le Bayon & Binet (1999). The amount of water runoff was noted every minute and the aliquot taken off per minute for analysis was as far as possible 500 ml. A runoff coefficient (Rc) was determined as the ratio between the collected volume and the volume of the rainfall precipitation corresponding to the contributive upslope area for each collector. Each water aliquot (500 ml or less) was filtered at 0.45 µm and the sample of sediment was then dried (40 °C). To make possible chemical analyses, the elementary sediment samples were pooled at every five minutes rainfall period. The INRA laboratories following the AFNOR norms analyzed organic nitrogen and organic carbon. Total phosphorus (TP) and total dissolved phosphorus (TDP) were determined colorimetrically after digestion using the molybdate acid procedure (Murphy & Riley 1962), in unfiltered and filtered extracts at 0.45 µm, respectively. Digestion was carried out by the addition of H_2SO_4 4N and $K_2S_2O_8$ to water samples, which were put in an autoclave at 120 °C for one hour. The difference between TP and TDP gave the amount of particulate phosphorus (PP). Organic phosphorus was determined by igniting soil sediment samples at 550 °C. After ignition, H_2SO_4 2N was added and the samples were checked over 24 h. Phosphorus was then colorimetrically determined and the difference between ignited and non-ignited samples gave amounts of organic phosphorus (Anderson & Ingram 1993). The water quality data were statistically analyzed using the non-parametric test of Mann-Whitney U (Minitab version 12 software).

Results

Erodibility of surface casts (Experiment 1)

Visual observations in the field showed that no cast transport occurred during the rainfall simulation even when casts were very dry, but only cast disintegration and transfers of particles. All parameters related to the morphology of casts were affected at the end of the simulated rainfall (Fig. 1). The type and the age of casts were two predominant factors that significantly controlled the variation of the surface area (S) (Kruskal-Wallis test, n = 60, 95%, $p = 0.000$ and 0.009, for type and age respectively) and the volume (V) (Kruskal-Wallis test, n = 60, 95%, $p = 0.000$ and 0.001, for type and age respectively) of casts during the rainfall. For ESA types, young ones lost a mean of 62.6% of their surface base, while oldest casts showed a high variability. Conversely, most old AN casts (63%) collapsed onto the ground as shown by their increased surface base ($\Delta S = +16.9\%$). Without exception, all casts flattened out by losing a few millimeters in height. Erodibility of casts significantly differed between age groups (Kruskal-Wallis test, n = 8, 95%, $p = 0.023$, Fig. 1).

As expected, young casts were first affected by the raindrop impact. For instance for AN casts, half of young casts were hit during the first five minutes (2.8 casts min^{-1}), while the deterioration of old ones was only observed in the last five minutes (1 cast min^{-1}). Although the erodibility was not significantly related to the type of cast (Kruskal-Wallis test, n = 8, 95%, $p = 0.13$), many ESA casts completely disappeared (60% and 10% for young and old casts, respectively) while AN casts were still present and just eroded, *i.e.* they had fuzzy features. The mean initial dry weight (105 °C) of casts was of 1.2 (± 0.2) and 1.3 (± 0.2) g for old and young ESA casts, and 4.2 (± 0.5) and 4.4 (± 0.6) g for old and young AN casts, respectively. The amount of matter lost from earthworm surfacecasts over the twenty minutes of rainfall reached a total of 26% (9% and 17% for ESA and AN casts, respectively).

The logarithmic regression gave the best estimation of the percentage mass lost relative to the initial mass (Fig. 2).

Soil losses from young casts were found to be inversely dependent on initial mass (regression, 95%, $r^2 = 0.56$, $y = -37.6\,x + 100.2$). However, for old casts, no signifi-

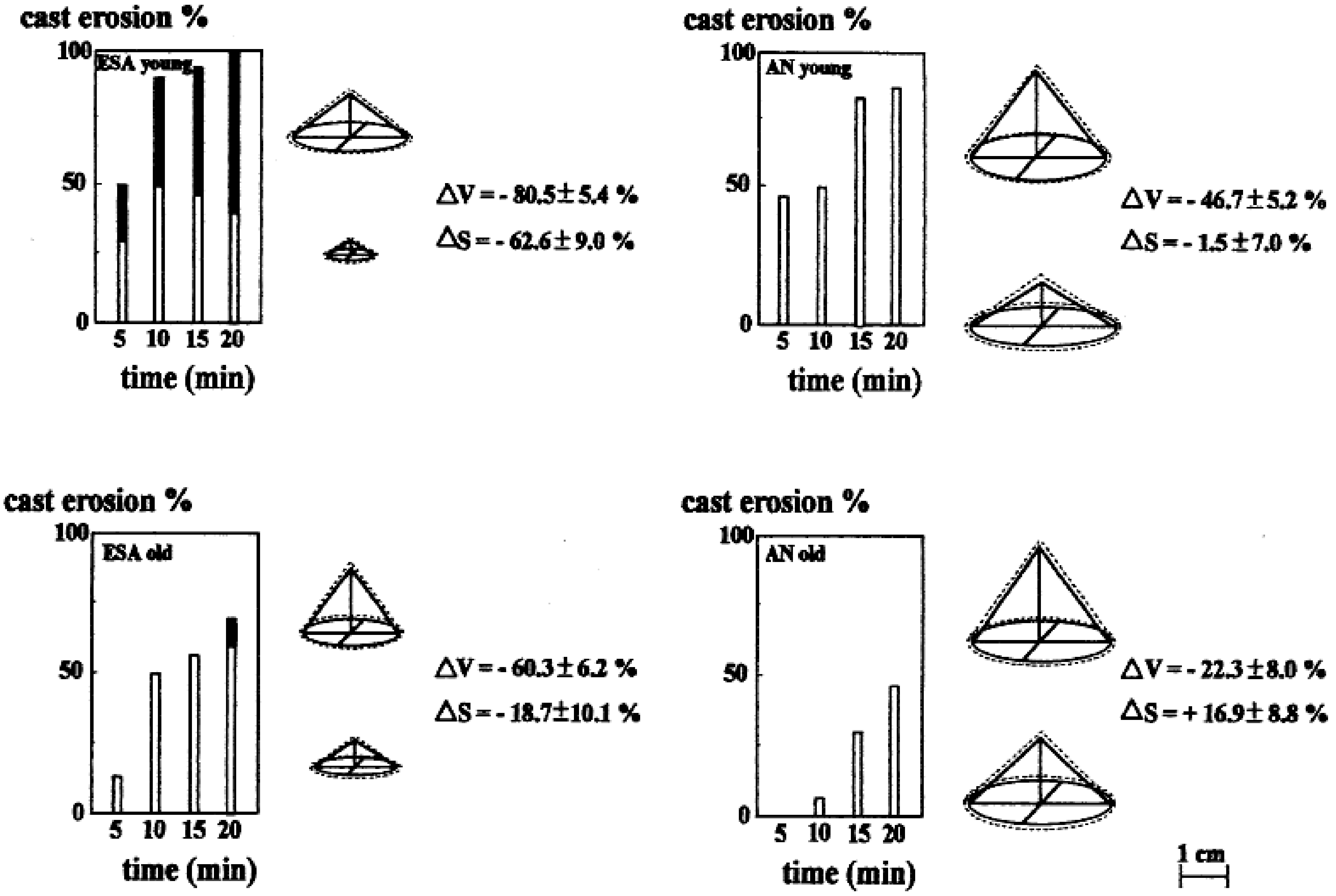

Fig 1. Cumulative percentage of cast erosion (histogram) and total variation of the surface (ΔS) and volume (ΔV) before and after the rainfall event. (Line: mean; dotted line: mean ± SE. Dark area: missing casts; white area: eroded)

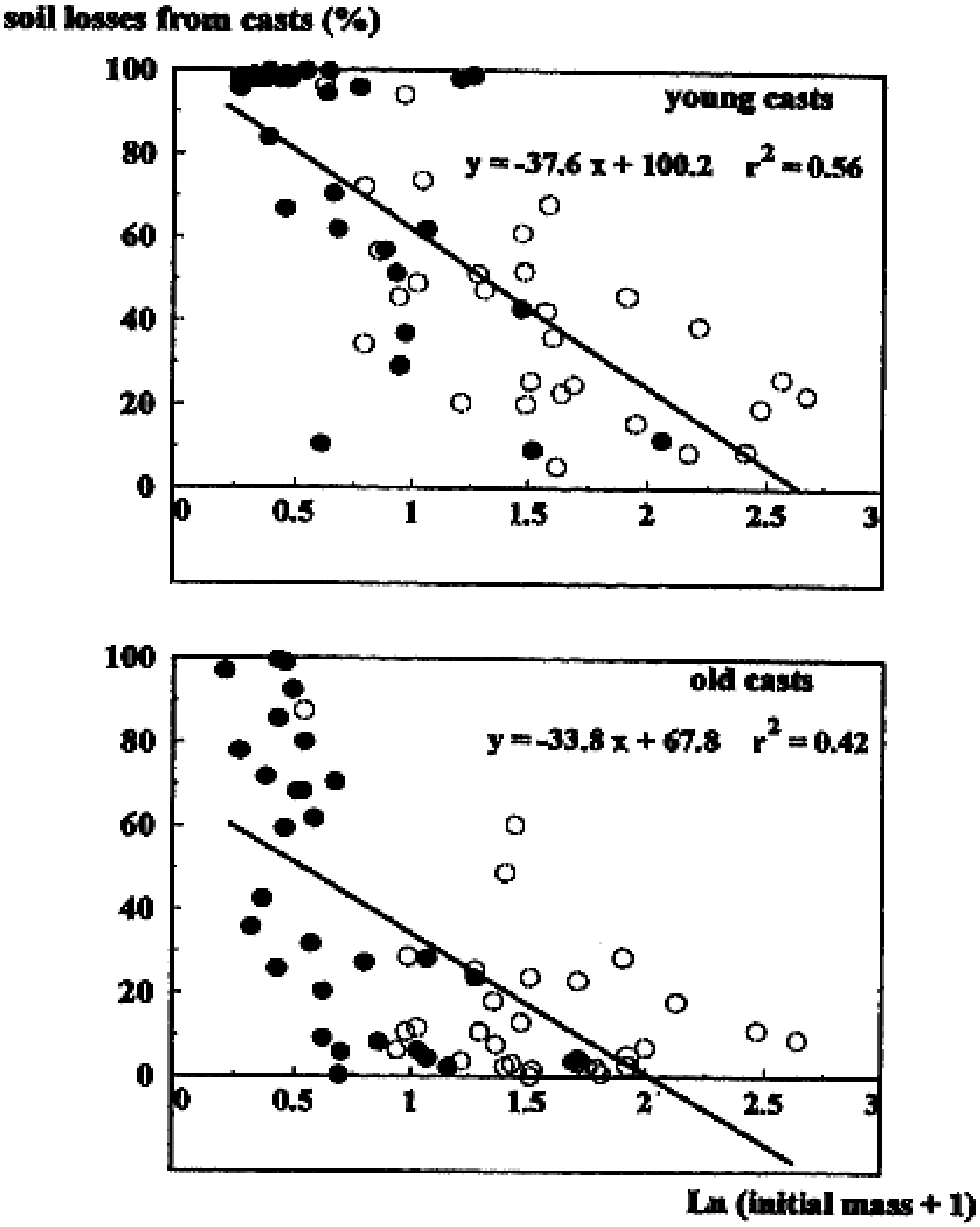

Fig 2. Regression of percentage of soil lost from casts against their initial mass (modified as Ln (x+1)) for young and old casts. (Black and white points: ESA and AN casts, respectively)

cant linear relationship was obtained (regression, 95%, $r^2 = 0.42$, $y = -33.8\ x + 67.8$). Many old casts lost a maximum of 30% of their initial mass when cast weight was greater than 1–1.5 g. Conversely, when old casts were initially less than 1–1.5 g, soil losses greatly varied from 20 to 100%. This suggests a difference of resistance against erosion between old AN and old ESA casts.

Contribution of surface casts to soil erosion (Experiment 2)

Cast erosion, water runoff and sediment transport. In the "cast erosion" plot, the abundance of surface casts progressively reached 761 casts m^{-2} (342.1 g m^{-2}) at the end of the 15-day period prior to the simulated rainfall experiment. The ESA casts were the most numerous compared to AN casts (76.5% and 23.5%, respectively). The soil covering by surface casts was then 24.6%. The cumulative sediment losses and runoff waters were closely related to the amount of precipitation and the rainfall intensity, as well as the presence of earthworm surface casts (Fig. 3).

A time-lag was observed between the beginning of the rainfall simulation and the first runoff waters collected that varied from 2 minutes for the control plot to 7 minutes for the plot with casts. Runoff and sediment transport were two to three times greater from the control plot than the plot with casts (26.7 l m^{-2} *vs* 10.1 l m^{-2} and 65.5 g m^{-2} *vs* 28.1 g m^{-2}, respectively). During the first hour, the rates at which water and sediment accumulated under the control plot (0.38 g min^{-1} *vs* 0.16 l min^{-1} and 0.51 g min^{-1} *vs* 0.24 l min^{-1} for V_1 and V_2, respectively) as well as under the plot with surface casts (0.37 g min^{-1} *vs* 0.07 l min^{-1} for V_1') were closely related. When rainfall intensity was increased (I_2), the rate of sediment loss increased more than the runoff rate and was in accordance with the increase of particulate phosphorus (PP) losses. A slight increase in the amount (+50%) was observed for both water and sediment curves under the plot with casts ten minutes before the end of the rainfall, corresponding to both an increase of soil erosion (0.85 g min^{-1} *vs* 0.54 g min^{-1} and 0.28 l min^{-1} *vs* 0.15 l min^{-1} for V_3' and V_2', respectively) and an increase of PP losses (from 0.56 mg P m^{-2} to 1.33 mg P m^{-2}). The runoff coefficient Rc was always lower under the plot with surface casts compared to those under the control plot (Rc of 11.2% *vs* 32.8%, and 23.8% *vs* 58.2%, for I_1 and I_2 respectively). Runoff coefficients almost doubled with a change in rainfall intensity from 37 to 50 mm h^{-1} for both control and cast plot (2.1 *vs* 1.8 times control values, respectively).

Nutrient transfers C, N, P. In order to determine the water quality of the runoff from the plots, phosphorus, nitrogen and carbon contents were analyzed. Because enough sediment was not available for analyses in the first minutes of the rainfall simulation, results from the plot with surface casts were obtained only after 35 minutes (Fig. 4). The whole nutrients recovered in the runoff waters showed higher amounts than the initial soil content. Organic carbon, as well as organic nitrogen were not significantly higher in the water runoff coming from the control plot than from the plot with casts (Mann-Whitney U-test, 95%, $n = 11$, $p = 0.527$ and $p = 0.107$, respectively). Nitrogen (4.6 ‰ to 3 ‰) and carbon (3.4 % to 2.7 %) contents declined with time during the rainfall simulation especially for the control plot.

Phosphorus enrichment of sediments was about similar from the two plots, except during the first 20 minutes (1.7–1.8 *vs* 1.2–1.4 mg g^{-1} for control and plot cast, respectively).

Organic phosphorus (data not shown) was found to be significantly higher during I_1 in water runoff coming from the control plot compared to the plot with surface casts (Mann-Whitney U-test, 95%, n = 11 and 10, $p = 0.0019$), while the contrary was observed during I_2 (Mann-Whitney U-test, 95%, $n = 7$, $p = 0.0047$). At the end of the rainfall simulation: (i) the soil covering by casts was half reduced (12.7%), (ii) a total of 153 g m^{-2} potential losses was either transported by runoff water or mixed with the soil surface matrix (97.4 g m^{-2} and 55.6 g m^{-2} for ESA and AN casts, respectively), (iii) sediment losses recovered when water runoff reached 65.5 g m^{-2} and 28.1 g m^{-2} from the plot without and with casts, respectively, and (iv) particulate phosphorus losses were 86.2 mg m^{-2} and 34.7 mg m^{-2} from the plot without and with casts, respectively.

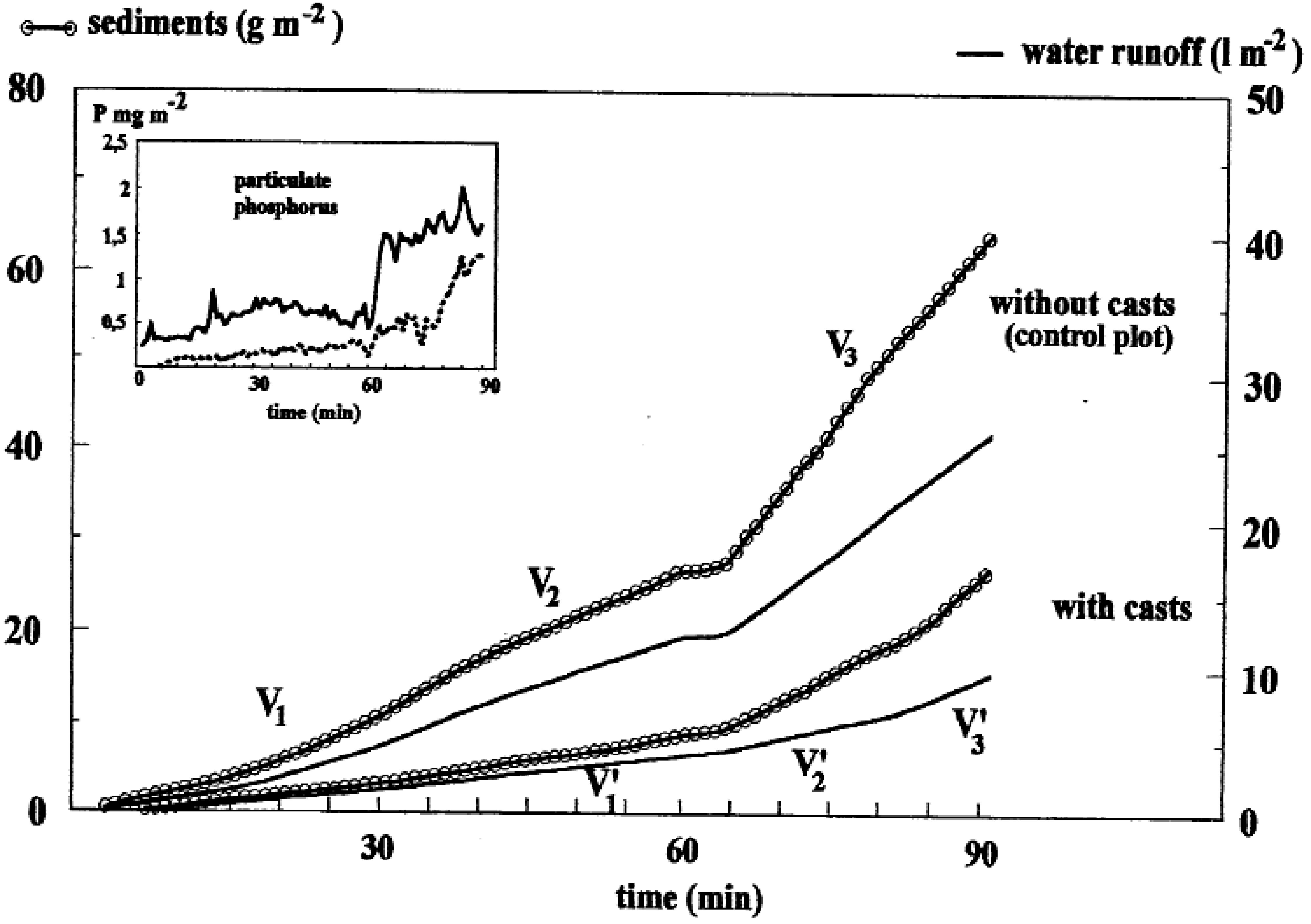

Fig 3. Cumulative losses of sediment, runoff and particulate phosphorus for the rainfall simulation. (I_1 and I_2: rainfall intensity; V: rate of sediment losses (g m^{-2} min^{-1}) and/or water runoff (l m^{-2} min^{-1}) for the three defined time periods)

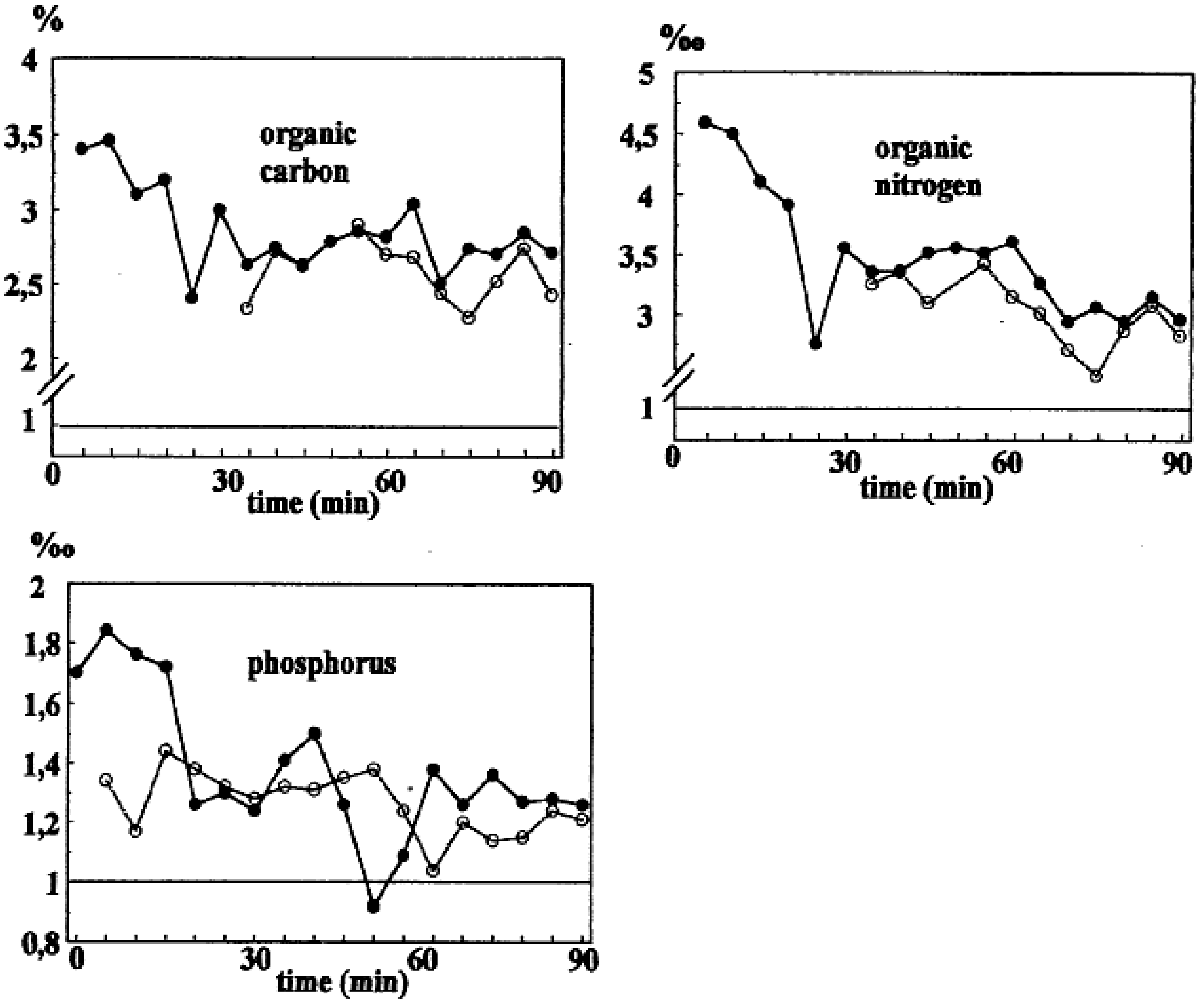

Fig 4. Total organic carbon, organic nitrogen and phosphorus content of runoff waters over the rainfall simulation period for control plot (line) and plot with surface casts (dotted line). (Lower dotted line: initial amount of the nutrient in the soil matrix)

Discussion

As expected from the literature, erodibility of earthworm casts was shown to be high for those that were either newly deposited on the soil surface or less than 5 days-old. This could be explained by their initial low stability compared to the uningested soil (Marinissen & Dexter 1990; Schrader & Zhang 1997), which increased during ageing and drying for example by fungal colonization (Parle 1963; Tisdall & Oades 1982; Molope et al. 1987) or by the formation of clay-polyvalent cation-organic matter (Shipitalo & Protz 1988). The greater water stability of 10–15 days old casts observed here is in line with the critical 10 days threshold previously observed in the field below which casts disappeared quickly and beyond which cast disappearance slowed down to half (Binet & Le Bayon 1999). The question raised is whether this 10 day period does or does not correspond to the time course of both mechanisms of stabilization that were observed by the authors cited above. Soil losses from casts were not explained by their initial mass when getting more than 10 d-old. A difference between AN and ESA casts in their resistance against erosion is suggested. As assessed by the base/height ratio (S/h), ESA and AN casts showed proportionally a similar initial conic shape when young (S/h = 3.8 ± 0.5 cm *vs* 3.3 ± 0.3 cm, respectively). With ageing, AN casts get a more flattened architecture than the ESA ones (S/h = 2.7 ± 0.2 cm *vs* 1.9 ± 0.2 cm, respectively). Two consequences for cast erosion may be expected: i) on the one hand, the surface of AN casts exposed to raindrop impact would be greater than for ESA casts and this would make help their erosion, ii) on the other hand, raindrop impact led to a top to bottom redistribution of the constitutive soil particles without any soil matter loss as it would happen for a more vertical architecture. This latter hypothesis seems to be more valid in our study. Moreover, the better resistance of AN casts against erosion might be explained too to their bulk density that was significantly greater than for ESA casts (1.44 ± 0.3 g cm^{-3} *vs* 1.25 ± 0.2 g cm^{-3}; Mann-Whitney U-test, n = 30, 95%, $p = 0.02$). However, not only the moisture and the mass but also parameters such as cast build-up and cast architecture seem to play a determinant role in the resistance of cast to erosion. Fine measurements of these parameters are still needed to get a better insight in the mechanisms of cast erodibility.

Two steps in cast erosion were observed *in situ* (Fig. 5).

As the rainfall began, the surface roughness caused by earthworm casts acted first as a physical brake, reducing water runoff. The water flow coming from the top of the plot stagnated behind the casts "micro-wall", creating small puddles that increased hypodermic infiltration in soil and percolation through the corresponding burrows, reducing it in turn. The time-lag of 7 minutes before the water runoff began from the plot with casts enforced the idea that casts create a natural barrier against runoff. Kladivko et al. (1986) also showed that an uneven and fragmented soil surface due to surface casts and burrow openings would reduce the susceptibility of a soil to crusting. Burrow holes were hand-closed on the control plot before the simulated rainfall, and we concluded that the burrows in the cast plot were partly opened and acted as a preferential pathway for water, affecting the infiltration rate, as shown by many authors (Ehlers 1975; Pitkänen & Nuutinen 1998; Francis & Fräser 1998). Then, the rainfall running, a slow deterioration of casts occurred whereby the finest particles were broken off the casts. Surface casts were then progressively dispersed till their breaking-down point, when they were quickly eroded and finally completely washed away, con-

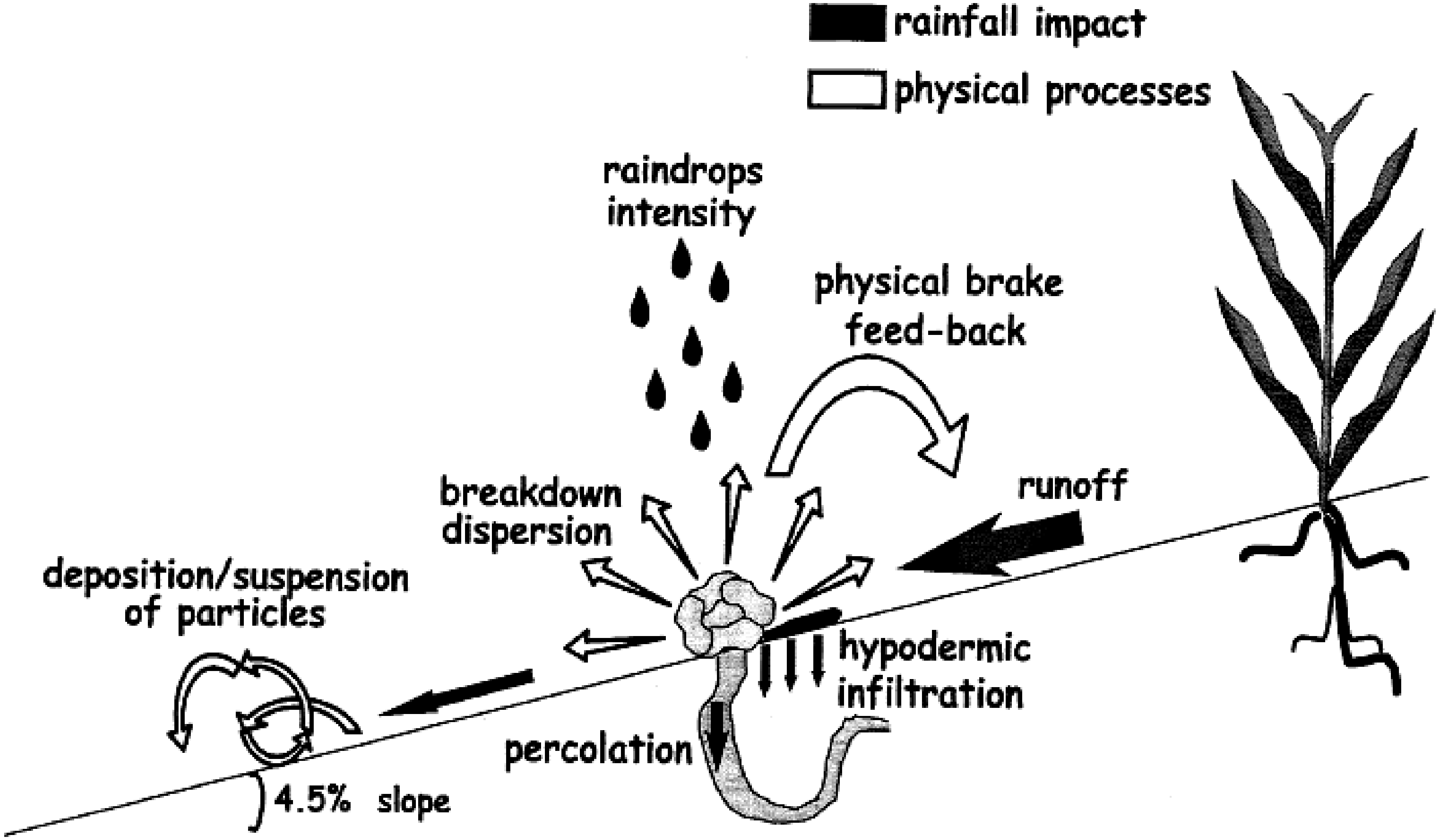

Fig 5. Synthesis of the interrelationships between earthworm surfacecasts and soil erosion by water runoff

tributing to soil movement and particulate transfers. It is paradoxical that despite the abundance of casts (25% of the plot area was covered by casts before the rainfall simulation) and an obvious cast erosion in the plot with casts, amounts of sediment and nutrient lost (C, N and P) in the runoff waters were at least twice as high without surface casts. This is in contrast to the study by Sharpley et al. (1979) who showed, that in small erosion plots (900 cm^2, that is 33 times smaller than our erosion plot) under a permanent pasture and with a slope of 13° (that is 23% compared to 4.5% in our case), losses of particulate phosphorus and sediment in surface runoff were higher in the presence of surface casts. Regarding these opposite results, the number of casts covering the soil surface just before performing the rainfall simulation need to be considered. In fact, in order for the casts to act as a physical barrier towards the runoff water, a minimal density of casts is probably needed. Further rainfall experiments on field plots varying in their cast abundance would answer this question. In addition, the nutrient content of sediment was greater than the initial content of the soil matrix, confirming the transport of large amounts of organic matter by runoff waters. Earthworm casts were found to contain a mean of 0.80 mg P g^{-1} (Binet & Le Bayon 1999), so a potential amount of 128.5 mg P m^{-2} can be expected to have been transferred by water runoff. However, the amount of particulate phosphorus (PP) recovered in the water runoff was only 34.7 mg P m^{-2}. Two hypotheses may be given: (i) either the gentle inclination of 4.5% in our plot made the soil particles and nutrients from casts move over only a few centimeters and/or mix with the soil matrix, (ii) or the finest particles from casts partly reached the water collector but were not detected in our analysis because of their small amounts compared to the higher amount of particles coming from the soil surface matrix. So, surface casts might be redistributed on short-distance through a successive deposition/suspension of soil particles according to the strength of gravity, *i.e.* bigger particles would sediment more rapidly than smaller ones. The slight increase in the amounts of sediment, water and particulate phosphorus under the plot with casts ten minutes before the end of I_2 led us to think that the cast breaking-down point may be reached at this moment and that a greater particulate and phosphorus transfer would have occurred if the rainfall simulation had not ended.

In conclusion, we did not demonstrate, unlike Sharpley et al.'s (1979) observations, that earthworm casts were a substantial source of sediment. In future, fine measurements of the cast architecture as well as measures of the dispersion index of casts could add to these results and allow a better understanding of the complex interactions existing between cast properties and physical mechanisms (soil particle detachment) in the erosion process. Further research should also focus on the use of markers (coloring, isotopic markers, etc.) to trace the origin of the sediment transferred by water runoff so that we can better track the transport of soil particles and quantify the soil erosion related to the bioturbative activities of earthworms at the soil surface.

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