Published in Biology and Fertility of Soils 30, issues 1-2, 7-13, 1999
which should be used for any reference to this work

Rainfall effects on erosion of earthworm casts and phosphorus transfers by water runoff

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Abstract We investigated whether, under a temperate climate and in a maize crop, earthworm casts could contribute to soil erosion and further favour the exportation of phosphorus by runoff waters. Recording of casts was made in compacted (wheel-tracks) and non-compacted inter-rows, for a 2-month period in spring. To assess the rainfall impact on cast evolution, half of the observation sites were protected against rain splash by a nylon mesh placed above the soil surface. The water runoff was collected and analysed for sediment contents and phosphorus concentration. The mean annual production of surface casts was calculated to be 34 kg (dry weight) year^{-1} kg^{-1} earthworm (fresh weight). Synchronization between cast erosion and rainfall events was shown under natural conditions (unprotected sites). The erosion rate was 4 times greater over rainy periods than dry ones, reaching 80% of cast numbers. It appeared that not the runoff effect but the splash effect, due to the kinetics of the drops, disrupted casts. Newly formed casts disappeared first, with the erosion rate decreasing twofold for casts more than 10 days old. Cast erosion and runoff, as well as worm casting activity, were greater under compacted sites than under non-compacted sites, indicating an influence of earthworms on soil erosion from compacted soils. The total phosphorus content was similar in casts and uningested soil (0.80 mg phosphorus g^{-1}). Potential phosphorus losses from cast erosion was calculated to reach 25–49 mg phosphorus m^{-2} per rainfall event depending on soil compaction. The amounts of particulate phosphorus recovered in water runoff after each rainfall event varied from 1 mg to 11 mg phosphorus. These results are compared and discussed.

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Key words Earthworm · Surface casts · Rainfall events · Soil erosion · Phosphorus

Introduction

The status of the soil surface influences water runoff and also soil erosion. Thus, soil-surface seals and crusts reduce water infiltration into the soil and induce erosion by increasing runoff (Boiffin and Monnier 1986). In addition to these physical characteristics, biological factors such as bioturbation by earthworms, i.e. their casting and burrowing activities, modify the soil surface (Scheu 1987; Blanchart 1990; Marinissen 1994). Under a temperate climate, cultivated soils with rows of plants aligned down the slope, especially in the case of steep slopes (>5%), lead to a greater risk of sediment transport during rainfall events. Two main factors act during rainfall: 1) the splash effect, whereby raindrops by their vertical impact pressures cause soil particles to fly into the air, and 2) runoff effect, whereby the flow of water across the land surface transports sediment (Nearing 1997). So, many fine particles and much organic matter might be eroded by such forces. It has been well-established that earthworms produce numerous casts deposited on the soil surface, and that casting activity is high during rainy seasons (Lee 1985; Nooren et al. 1995; Binet and Le Bayon 1999). Roose (in Nooren et al. 1995) suggested that surface casting by earthworms in combination with lateral transport of fine soil material by water runoff could have contributed to the erosion of Ivory Coast surface soils, and in particular to the formation of sandy coarser surface soils. In addition, a previous study in grasslands by Sharpley and Syers (1976) showed that earthworm casts contain more soluble phosphorus than uningested surface soil.

So, the main aims of our study were to determine whether, under temperate, cultivated soils, earthworm surface casts might contribute to soil erosion following rainfall events, and also increase nutrient losses in water runoff, in particular phosphorus losses. To answer these questions, we looked first at the production of surface casts and its spatial/temporal dynamics in relation to raindrop impact and runoff effect of several rainfall events. Worm casts and water samples were then analysed for their phosphorus content.

Materials and methods

The study was established under a temperate climate on a cultivated plot located near Rennes, in Brittany (NW France). The field site has a gentle slope of 4.5% and had been under maize with rows of plants aligned down the slope. Observations and measurements were made in spring for a 2-month period (March–May 1996) following the autumn crop harvest.

The cultivated soil supports a quite abundant earthworm community: 275 individuals m^{-2}, biomass of 100 g m^{-2}. Among the six species recorded, two were dominant: the endogeic *Aporrectodea caliginosa* and the anecic *Lumbricus terrestris* (69% and 11% of earthworm numbers, and 26% and 58% of the earthworm biomass, respectively). Rainfall and temperature data were gathered over the 2-month period (Fig. 1). Four rainfall events and two dry periods (without any rain) were defined and further analysed for cast production and cast deterioration. Characteristics of each event are listed in Table 1. More details on the plots, rainfall events and earthworm populations are given in an earlier paper (Binet and Le Bayon 1999).

To track cast production and cast disintegration over two modalities of soil compaction, a total of eight observation sites were defined from four inter-rows of maize, i.e. two non-compacted (soil bulk density of 1.25 g cm^{-3}) and two compacted (wheel-tracks, soil bulk density of 1.50 g cm^{-3}) rows, with two observation sites per inter-row (one at the top and one at the bottom). The length of each inter-row taken into account for studying casts was 25 m. A ditch situated just above the observation sites at the top of the inter-rows prevented the passage of runoff water from above the plot. So, the runoff effect of each rainfall event on cast disintegration was determined by comparing cast evolution at the top and at the bottom of each inter-row. To assess the vertical splash erosion of rainfall on casts, half of the observation sites were permanently (except during cast recording) protected against rain splash by a nylon mesh (2 mm) placed 10 cm above the soil surface (Fig. 2). As previously described by Binet and Le Bayon (1999), a grid of 2×0.75 m, comprising 585 units of 5×5 cm, was used to locate casts and record their date of appearance and date of disappearance. Observations were made every day during rainy periods and at 3-day intervals on others days during the 2-month period. To relate morphology to age, the three morphological types of casts defined earlier by Binet and Le Bayon (1999) were used: 1) moist and brown type, i.e. casts were bright and soft to the touch and had a fresh appearance, 2) dry and whitish type, i.e. casts were light brown to whitish and were hard to the touch, 3) eroded type, i.e. casts had indeterminate features and most often were moss-covered or colonized by white fungi. Mann-Whitney U-tests were performed to assess splash and runoff effects of rainfall events on cast production and cast erosion (Minitab version 8 software).

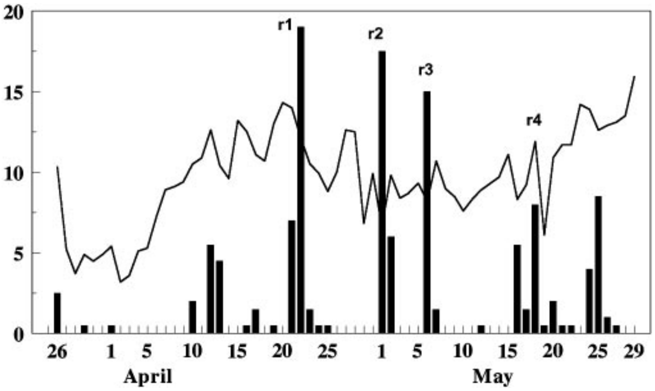

Fig. 1 Temperature (°C; *line*) and precipitation (mm; *histogram*) gathered during the 2-month study. *r* Rainfall event

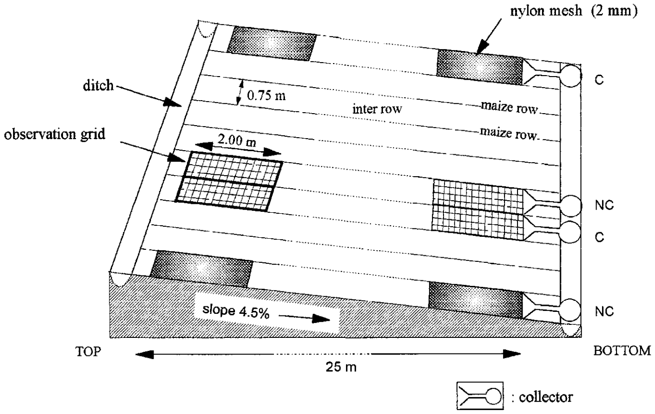

Fig. 2 Scheme of the experimental plot. *NC* Non-compacted inter-rows, *C* compacted inter-rows

For each inter-row, in accordance with Wischmeier's proposal (1976), the surface runoff plot was 25 m in length by 0.75 m in width, this latter distance corresponding to the space between two maize rows. At the bottom, water collectors were installed facing each of the four inter-rows studied. The water collectors comprised a large container (60 l) with a small reservoir inside (5 l) to collect small volumes of water. An extension (Y shape) was attached to the container. The latter was built of two PVC plates

Table 1 Rainy periods (*r1, r2, r3, r4*) and dry periods (*d1, d2*) defined for studying cast deterioration and soil erosion. Runoff water was collected beside each inter-row. *Pt* Total precipitation, *Imax* rainfall intensity, *C* compacted inter-rows, *NC* non-compacted inter-rows

Periods	Time (days)	Protected sites		Unprotected sites		Imax (mm h^{-1})	Pt (mm)
		NC	C	NC	C		
d1	8	–	–	–	–	–	–
r1	5	400 ml	1200 ml	375 ml	500 ml	15	19
r2	4	480 ml	620 ml	375 ml	470 ml	20	17.5
r3	8	350 ml	780 ml	300 ml	550 ml	5	15.0
d2	7	–	–	–	–	–	–
r4	5	300 ml	620 ml	170 ml	510 ml	25	8.0

70 cm in length connected with a rubber band to a 50-cm-long square pipe. The system was designed by Gascuel-Odoux et al. (1996). Water runoff was collected as soon as possible after rainfall or within 24 h, and was filtered through a 0.45-µm mesh. Total phosphorus and soluble phosphates in the extracts were determined colorimetrically with the molybdate-ascorbic acid procedure (Murphy and Riley 1962).

Fresh casts (24 h old) were collected 4 times at 2-week intervals: 14 April, 3 May, 17 and 29 May, from the experimental plot for total phosphorus analysis. Two types of casts were visually distinguished: the bigger ones were supposed to be produced by the anecic species (AN) *L. terrestris* which was the only anecic species on the plot, and the others either by endogeic species or small anecic worms (ESA). In addition, uningested surface soil collected at 0–5 cm depth was taken as a control. All samples were stored at 4 °C. Two methods were used for analyses of total phosphorus: the molybdate-ascorbic acid procedure of Murphy and Riley (1962) and the X-ray fluorescence spectrometry method. Phosphorus contents in both water extracts and soil samples were statistically analysed using the Mann-Whitney U-test (Minitab version 8 software).

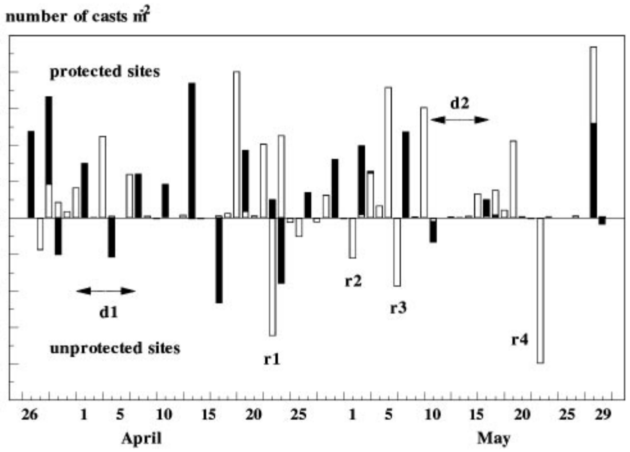

Fig. 3 Temporal dynamics of earthworm casting. The differences in cast production (*black area*) and cast disappearance (*white area*) between protected and unprotected sites are indicated. *d* Dry period, *r* Reinfall event

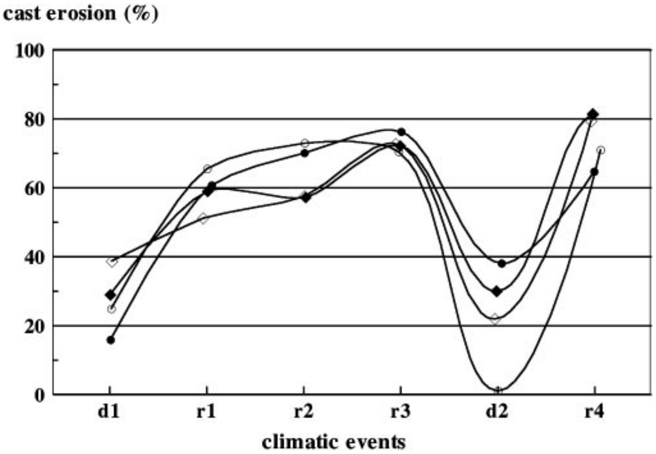

Fig. 4 Runoff and water splash effects on cast erosion. ◆—◆ No runoff, no water splash; ○—○ water splash; ●—● water splash and runoff; ◇—◇ runoff. For abbreviations, see Figs. 1 and 2

Results

Over the 2-month study period, similar temporal dynamics of cast abundance were observed from unprotected and protected sites, casts being in general more numerous on protected sites. Because cast abundance in situ depends on both cast production and cast erosion, we further compared the production and the disappearance of worm casts between rain-protected sites (artificial conditions) and unprotected sites (natural conditions; Fig. 3). Both daily production and disappearance of surface casts were basically greater and more regular from protected sites, i.e. without rainfall impact, than from unprotected sites. In contrast, peaks of casting activity and cast disintegration were most often observed under natural conditions (unprotected sites). As the temperature increased and the first rainfall occurred (10–15 April), cast production was boosted (data not shown). A higher average daily production of casts was found under protected than unprotected sites [18 vs 15 casts m^{-2}, i.e. 10.4 vs 8.6 g m^{-2} on a dry weight (d.m.) basis]. Greater numbers of newly formed casts were also found after each rainfall event, i.e. under natural conditions, after the first rainfall event (r1; 18 casts m^{-2}), and without raindrop impact after the second and third rainfall events (r2 and r3; 19 casts m^{-2}, and 24 casts m^{-2}, respectively). After the fourth rainfall event (r4), cast production increased in the protected sites with a time lag (26 casts m^{-2}), probably because of rain falling continuously at this time.

Under natural conditions, raindrop impact was shown as a factor determining cast disintegration over r1, r2 and r3 (losses from unprotected sites of 33 casts m^{-2}, 12 casts m^{-2} and 19 casts m^{-2}, respectively). For r4, which was the most intense rainfall, obvious cast erosion (approximately 40 casts m^{-2} on 22 May) was also observed, but with a time-lag of a few days (Fig. 3). In contrast, it was observed that the disappearance of casts occurred on a regular basis from protected sites, irrespective of the rainfall events. For all observation plots, the erosion rate of worm casts showed a generally similar pattern through the climatic events that occurred over the 2-month period (Fig. 4). In particular, the rate of cast disappearance was about 4 times greater over rainy periods than dry ones. The cast erosion reached a maximum of 80% at the end of the three successive rainfalls r_1, r_2, and r_3 and for the most intense rainfall, r4 (Fig. 4). Pair-wise comparisons of splash and splash-runoff effects as well as runoff and no runoff no-splash effects, showed no significant difference on the erosion rate, i.e. runoff impact did not have an impact on cast erosion in our study. However, we noted that the erosion rate of casts was often higher when splash effect occurred, although differences were not significant (63% vs 50% for r1 and 65% vs 58% for r2). Thus, it appeared that the kinetics of raindrops were mainly responsible for casts disappearing. In addition, it is important to note that numerous casts disappeared during the calm-weather periods without raindrop or water runoff influences. This could be explained by other climatic factors like windy or foggy days (data were not gathered in our study). Regarding the effect of soil compactness (data not shown), cast loss from protected plots was always higher (discrepancy of erosion rate between compacted and non-compacted soils of 20%) on compacted inter-rows during rainfall events, this being apparent when comparing the top and bottom of inter-rows. But from non-protected inter-rows, greater cast erosion under compacted soils was only observed at the bottom of the maize inter-rows, i.e. when runoff events occurred, and especially for the intense rainfall events (r3 and r4).

We looked at what sort of casts were eroded during dry and rainy periods (Fig. 5). For newly formed casts, highest numbers disappeared under protected compared with unprotected sites. Most of them were removed during rainfall (r2, r3 and r4). During dry periods 1 and 2 (d1, d2), it could be noted that cast disappearance concerned only fresh ones. The erosion of dry casts was observed for r1 and r4, only. During the first rainfall event (r1), more dry casts disappeared under unprotected sites than protected sites (67% and 46%, respectively), while for r4, disappearance of dry casts was 3 times higher under protected sites. The erosion of higher numbers of dry casts during r1 was probably due to the preceding long dry period, leading to a notable increase in dry casts and lower numbers of fresh casts in the field. The great erosion of dry casts during r4, especially from protected sites, was due to the high intensity of the rainfall. Differences between protected and non-protected sites will be discussed below. Eroded casts disappeared in the same low proportion under both treatments with or without the influence of rainfall. We calculated that the mean life-time of casts was similar (no significant difference) between unprotected and protected plots (7 and 8 days, respectively). The erosion rate of younger casts (i.e. <10 days old) was higher from protected sites, while it was 2 times lower under both protected and unprotected areas for older casts (more than 10 days old).

Both colorimetric and spectrometric methods gave similar total phosphorus contents in earthworm casts and in uningested soil (Table 2). Total phosphorus values between soil samples and casts were not significantly different ($n=4$, $(W)=21$, $P=0.74$ for soil vs ESA casts; $n=4$, $W=19.5$, $P=0.77$, for soil vs AN casts). In addition, similar phosphorus contents ($n=4$, $W=17$, $P=0.89$) were found in AN casts and ESA casts. The colorimetric determination indicated greater amounts of phosphorus (a mean of 0.85 ± 0.02 compared to a mean of 0.76 ± 0.01), that led to discussion of the most suitable method of phosphorus analysis.

The volume of water collected at the bottom of compacted areas (Fig. 6) was significantly higher than that of non-compacted areas ($n=8$, $W=99$, $P=0.0007$), while no significant difference appeared between protected and unprotected sites ($n=8$, $W=80.5$, $P=0.21$). This latter result was reasonable because nylon mesh protection was only efficient for a length of 4 m per inter-row. Variations in the phosphorus concentration of runoff water were observed over the four rainfall events (Fig. 6). However, a similar phosphorus pattern could be observed within the two compacted inter-rows, and this differed from the pattern of the non-compacted inter-rows. In particular, the content of soluble phosphorus was almost nil in water runoff collected from compacted soils. Statistically, compacted inter-rows released more total phosphorus, especially during r4 (16.4 mg l^{-1}). To assess the nutrient discharge in the water runoff, phosphorus concentrations (mg l^{-1})

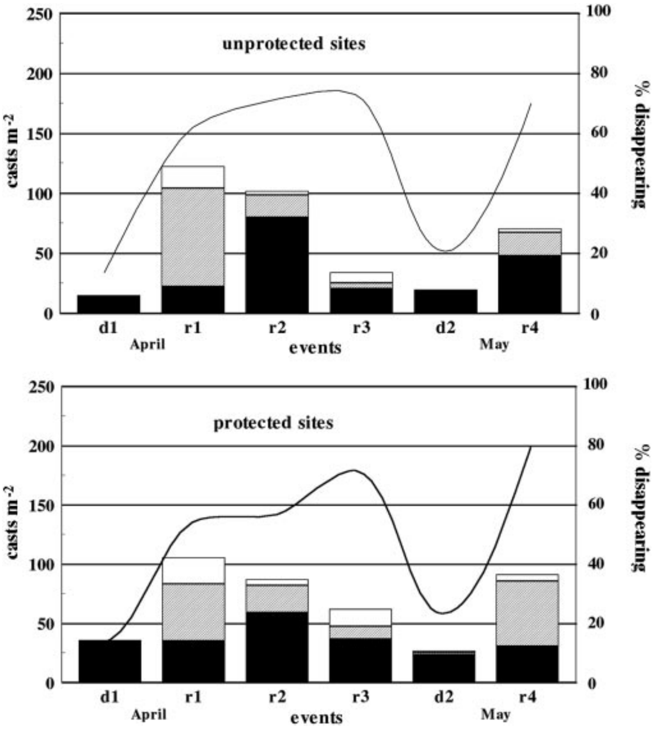

Fig. 5 Gross (*histogram*) and relative (*line*) disappearance of casts in relation to d1, d2 and r1–r4 for unprotected sites and protected sites. *Dark area* moist and brown casts, *shaded area* dry and whitish casts, *white area* eroded casts. For abbreviations, see Figs. 1 and 3

Table 2 Total phosphorus (*P*) content (mean ± SE) in casts and uningested soil determined by spectrometric and colorimetric methods. Within columns, values followed by the *same letters* are not significantly different at $P<0.05$ *AN* Anecic species, *ESA* endogeic or small anecic species

Sample	Spectrometry (mg P g^{-1})	Colorimetry (mg P g^{-1})
Soil	0.87 ± 0.03^{a}	0.75 ± 0.02^{a}
AN	$0.83 \pm 0.02^{a,b}$	$0.75 \pm 0.02^{a,b}$
ESA	$0.84 \pm 0.01^{a,b}$	$0.77 \pm 0.01^{a,b}$

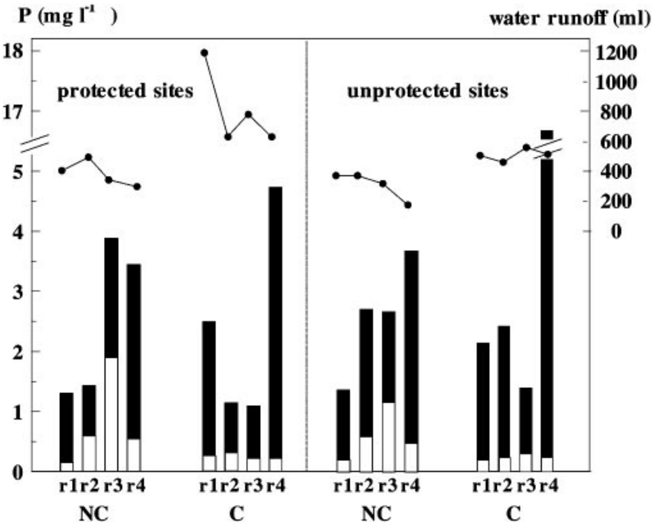

Fig. 6 Water runoff and phosphorus (*P*) concentration (mg l^{-1}) in water runoff over r1–r4 both under protected and unprotected sites. *Line* Water volumes, *black area* particulate P, *white area* soluble P

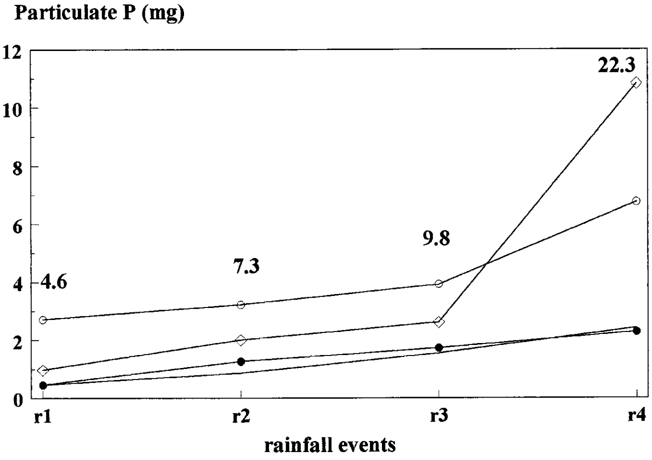

Fig. 7 Cumulative release of particulate P for each inter-row (for r1–r4). ●—● Unprotected, NC, ◇—◇ unprotected, C, —— protected, NC, ○—○ protected, C. The *numbers* along the top of the curves are cumulative totals for P losses from the four inter-rows during r1, r2, r3 and r4. For abbreviations, see Figs. 1, 2 and 6

were converted into phosphorus amounts (mg), allowing the calculation of particulate phosphorus (total phosphorus minus soluble phosphorus). The cumulative release of particulate phosphorus, i.e. phosphorus linked to soil particles from r1 to r4 rainfall events, are shown in Fig. 7. We noted soil detachment at the end of the succession of rainfall events, as indicated by the particulate phosphorus value of 9.8 mg. More important was the relationship between soil erosion and rainfall intensity observed during r4 (25 mm h^{-1}). In fact, during r4 the particulate phosphorus losses reached 22.3 mg, i.e. 4 times greater than between r1 and r2 or r2 and r3, indicating an obvious impact of rainfall on soil erosion. In addition, for all the rainfall events, losses of particulate phosphorus were significantly higher in compacted areas ($n=8$, $W=43$, $P=0.01$).

Discussion

Surface-cast production showed great spatial and temporal variability. Its assessment at the field scale was difficult because of the irregular distribution of earthworms in the maize field that was related to the presence of food like maize roots or silage residues, as shown by Binet et al. (1997). Consequently, we noted many “hot spots” of cast production on the plots that indicated that the worms aggregated in particular areas. In addition, as soil compactness leads to more soil ingested by earthworms, we have previously observed heterogeneity in the spatial distribution of earthworm casts, both along the length and the width of inter-rows (Binet and Le Bayon 1999). From our data, we calculated that surface-cast production was 34 kg (d.w.) year^{-1} kg^{-1} earthworms (f.w.) with the anecic *L. terrestris* and endogeic *A. caliginosa* as dominant species of the community. This is considerably higher than the value of 23 kg (d.w.) year^{-1} kg^{-1} earthworms (f.w.) estimated from a Mediterranean grassland for a monospecific community of *Scherotheca gigas mifuga* (Bouché and Al-Addan 1997). Our value is from a direct calculation based on the actual production of surface casts that we measured for the 2-month study, while Bouché and Al-Addan’s estimate was based on a surface casting activity of 8% of the total cast production. Mild temperatures and soil moisture that prevail after rainfall events provoke great casting activity. Nooren et al. (1995) also pointed out that casting is stimulated by soil moisture.

The synchronization between the vertical impact of raindrops and cast disintegration was pointed out by Al-Durrah and Bradford (1982) and Terry (1998), who described soil dispersal mechanisms during drop impact, and illustrated several of them with photographic and video techniques under laboratory splash tests. The soil particulate dispersal that they observed could explain cast erosion during a rainfall event. No runoff effect was shown by our experiment because the amounts of precipitation were not sufficient to cause cast erosion. Our study period, which was particularly water deficient, was not really suitable. Most of the casts that disappeared were newly deposited, as indicated by their low stability (Shipitalo and Protz 1989) while some of them became stable when they were more than 10 days old (Binet and Le Bayon 1999).

Mesh-protection against rain splash was shown to favour cast production by continuously maintaining higher soil moisture; this was apparent when we took off the nylon meshes. The water was sometimes held up (ponded) on the mesh, and the weight of the water tended to loosen the mesh. Thus, nylon mesh affects the way that water impacts the soil, which could explain the vigorous cast erosion and the time-lag observed during r4 under protected areas. We concluded that the mesh induced a bias in our experiments. Because of this bias, the estimation of cast erosion by comparing cast abundance between protected and unprotected plots, as done by Nooren et al. (1995), was not an appropriate method. To cancel this bias, we would have had to place nylon-mesh protection above the soil surface just before a rainfall event and then remove it, which would have required our permanent presence on the plot.

We also showed that many factors played a role in cast disintegration: 1) intensity of rainfall and amounts of precipitation, 2) the presence or absence of a dry period before the rain, 3) the cumulative effects of several rains. Parsons et al. (1994) observed that for two successive rainfall events (E1 and E2), the antecedent soil moisture level was higher and soil crusting was better developed in E2 than in E1, which led to a lower infiltration rate during E2. Similarly, our experiment indicated that each rainfall event was independent from the others and had to be placed in a temporal context to understand 1) when and how casts disappeared and, 2) which type of casts were affected.

Runoff was twice as high in compacted areas, and the collected waters contained higher amounts of particulate phosphorus than those from uncompacted areas, which confirmed a greater risk of soil erosion in the former. Considering that: 1) with an increase in soil compaction of 20%, individual casting activity was twice as high (Binet and Le Bayon 1999), and 2) cast erosion was higher; under compacted plots than uncompacted plots, we concluded that there earthworms actually contribute to soil erosion. For each of the four rainfall events, potential phosphorus losses from cast erosion were calculated to reach 25 mg and 49 mg phosphorus m^{-2} rainfall $event^{-1}$ in non-compacted inter-rows and compacted inter-rows, respectively. We then compared the phosphorus losses from surface casts with the amounts of particulate phophorus recovered in the water runoff. It must be noted here that water runoff collected at the bottom of each inter-row corresponded to a surface runoff of 19 m^2 (25 m in length × 0.75 m in width). The amounts of phosphorus recovered in the water runoff after each rainfall event varied from 1 mg to 11 mg phosphorus for 19 m^2, depending on the maize inter-rows. This corresponded to 0.1–2% of the phosphorus losses from casts, which seemed very low. So, we did not find a relationship between earthworm casting activity and the phosphorus content of water runoff. This can be explained by the following. Once casts disappeared, i.e. once the biological soil aggregates disappeared, the question was whether the soil particles were transferred by water runoff or if they mixed with the surface soil matrix. For our study conditions, which included a gentle slope and weak runoff during the 2-month period, we suggest that during rainfall events, most of the cast material moved over a few centimetres and/or mixed with the soil surface matrix, but did not reach the water collectors. During dry periods, we observed the stabilization of many casts by fungi or only moss colonization, as was observed by Tisdall and Oades (1982) and Molope et al. (1987). These stabilized casts were potential sources of phosphorus which may be reallocated with time.

In conclusion, we found that earthworms greatly contribute to soil erosion, especially from compacted soils, by their casting activity. Rain intensity and amount of precipitation interact and make it difficult to define which of these factors is preponderant. Further experiments based on simulated rainfall are needed to solve this problem, so that we can determine whether, once casts disappear, transfers of cast particles occur or not. Also, the phosphorus content of casts is needed to assess which chemical forms may contribute to the release of this nutrient (for instance as available phosphorus).

Acknowledgements This research work was part of the CNRS-INRA program on phosphorus and was supported by grants from the Ministère français de l'Environnement et la Région Bretagne. Phosphorus analyses were made by the laboratories of CNRS UPR 4661 Géosciences, and the ENSP in Rennes. The authors thank Dr C. Gascuel-Odoux for her advice in the set-up of the experiment and M. Lefeuvre for his technical assistance. We also gratefully acknowledge two anonymous reviewers for providing critical comments that helped improve this paper.

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