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Annual variations in earthworm surface-casting activity and soil transport by water runoff under a temperate maize agroecosytem

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Abstract

Investigations were conducted on both the annual patterns of earthworm casting activity and the annual variations in soil and phosphorus (P) transfers by water runoff, under a temperate maize crop, to determine whether there is any time synchronism over the year between these processes that could increase risk of soil erosion. Cast dynamics were measured at 15-day intervals for 1 year. Phosphorus forms were determined in runoff waters and the sediments collected were analyzed for nitrogen (N), carbon (C) and P contents. As long as there was no crust at the soil surface, no runoff was observed. Once the sealing crust formed, the soil erosion began. After the rainstorm events in August, soil erosion already reached 70% of the total soil loss that occurred over the crop year. A total of 140 g m^{-2} $year^{-1}$ of sediment was lost by the end of the year. A time synchronization was observed between tillage practices and highest cast productions over the year, which were then interrupted for up to 5 weeks after both ploughing and crop harvest. In particular, the absence of anecic casts onto the soil till September underline that *Lumbricus terrestris* was most affected by ploughing. The likelihood that earthworm casts contributed to soil erosion was enforced by the correlation between the timing of cast disappearance and the increase in sediment transfers for rainstorm events observed in summer, as well as for long rainy period in fall/winter. However, we could not outline a systematic correlation over the year but just for defined periods. Particulate soil erosion and P amounts in runoff waters decreased (55–2 g m^{-2}, and 19–5 mg of P losses m^{-2}, respectively) through the crop year. However, the content of organic matter in sediment increased (2.54–5.16%) compared to the initial soil (1.8%), as well as the P concentration (1.1–1.6 mg g^{-1}). © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Soil erosion; Water runoff; Earthworms; Surface-casts; P; Maize crop

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1. Introduction

The focus on agricultural runoff and sediment transports has intensified in recent years. Soil crust formation under rainfall reduces infiltration rate and increases runoff and erosion, especially for loamy soils. This physical process can be counteracted by soil macrofauna activity, e.g. earthworms, that also greatly influences soil structure, porosity as well as the soil surface features.

How earthworms affect soil erosion is not clear. The general idea from the literature is that the presence of earthworms decrease runoff up to 2–15 times by increasing soil water infiltration (Ehlers, 1975; Joschko et al., 1989; Edwards et al., 1990; Kladivko and Timmenga, 1990; Bouché and Al-Addan, 1997; Willoughby et al., 1997). In fact, earthworms enhance macroporosity by the burrows network or continuous channels they create, and the persistence of open burrow holes at the soil surface lead to decrease runoff from crusted soils (Roth and Joschko, 1991). Also, by their surface casting activities (i.e., egesting soil, burying organic matter), they enhance the soil surface roughness and then reduce soil crusting, which in turn improve water flow into the soil (Kladivko et al., 1986).

However, earthworm casts that are deposited on soil surface are subject to splash erosion (Van Hoof, 1983), and the fine soil materials as well as plant nutrients N (Parle, 1963; Binet and Tréhen, 1992), P (Graff, 1970; Sharpley and Syers, 1976), and K (Tiwari et al., 1989) they contain, are exposed to be easily detached and transported during rainfall events. Hence, surface-casts were shown to be a potential source of particulate and dissolved P in surface runoff waters from a permanent pasture (Sharpley and Syers, 1976). From previous studies over a short 2-month period in spring, during a fallow-phase rotation, earthworm surface-casts were also expected to improve soil erosion especially under compacted soils, where both casting activity and water runoff volumes were highest (Binet and Le Bayon, 1999; Le Bayon and Binet, 1999).

During rainfall events, surface-casts are first hit by the raindrops. So, regarding soil erosion by overland flow, they have to be washed away before the opening hole of the underneath burrow can act as a preferential pathway for water flow. Our hypothesis is that under certain conditions of high risk of soil erosion (e.g. steeped slope, row-cropping, compacted soils, low content of soil organic matter), earthworm surface-casts contribute to soil erosion and particles transfers by runoff waters.

The present study deals with observations at a year scale for a maize agroecosystem that presents soil erosion hazards. Our objectives were: (i) to quantify annual earthworm casting dynamics with respect to climate events, crop growth and land use practice, (ii) to relate the cast disappearance with soil erosion process as measured by the particulate P transfers in water runoff, in order to (iii) determine whether or not there is any time-synchronism over the year between these biological and physical processes.

2. Materials and methods

The field site is located near Rennes (Brittany, NW France). The climate is temperate and the plot has a gentle and regular slope of 4.5%. The soil is loam (70%) with low contents of organic matter (1.8%) and clay (15%). pH (water) is 6.4. Two earthworm species are dominant: the endogeic *Aporrectodea caliginosa* and the anecic *Lumbricus terrestris*, corresponding to a total biomass of 100 g m^{-2} (Binet and Le Bayon, 1999). The plot was cultivated to maize in 1994 and 1995. After the maize harvest in autumn 1995, crop residues were left to cover the land and the field was kept unploughed for 1 year. Then, a leguminous plant (*Phacelia* sp.) was sown in October 1996. In April 1997, the soil was ploughed and maize plants were sown on 22 April in rows running downslope. The spacing between rows was 0.75 m. No fertilizer was applied and the weeding was regularly made by hand. Crop harvest (maize ensilage) occurred on 24 September 1997, without residues on the soil surface, and a similar tillage as in 1997 was done in April 1998.

Observations and measurements were made for 1 year, from April 1997 to April 1998. A total of five similar inter-rows of 25-m length and 0.75-m width were chosen to assess both cast production and water runoff. To track surface-cast dynamics, a grid of 2×0.75 m, composed of square units of 5×5 cm, was used to count casts and to record their type and age at 15-day intervals. The position of the grid was randomly chosen on each inter-row in order to take into account the spatial heterogeneity of soil characteristics and casting activity previously demonstrated (Binet and Le Bayon, 1999). As described earlier by Le Bayon and Binet (1999), two types of casts were visually distinguished: the bigger ones produced by the anecic species *L. terrestris* (AN), and the others either by endogeic species and/or small anecic worms (ESA). Cast abundance on the field site is the result of both production and disappearance of earthworm surface-casts. When the difference in cast number between two successive dates of cast observation was positive, it was then considered as a minimal production of surface-casts, while when the difference was negative, it was then assumed as a minimal erosion of surface-casts. The mean weight (dry weight basis) of both AN casts and ESA casts was determined on 100 casts that were collected randomly in the field (AN casts: 1.00 ± 0.23 g and ESA casts: 0.28 ± 0.07 g).

Temperature, rainfall intensity and amount of precipitation were recorded at the meteorological station INRA Le Rheu near (2-km far) the study plot. Fig. 1 shows three water deficiency periods, one in April 1997 and the others in July and September. February 1998 was also a dry month, but no water deficit occurred.

Runoff collectors were installed at the bottom of each of the five inter-rows according to a system designed by Gascuel-Odoux et al. (1996). After the crop harvest, we had to take into account the heterogeneity of the soil surface created by farm equipment during the harvest. Hence, collectors were reinstalled facing

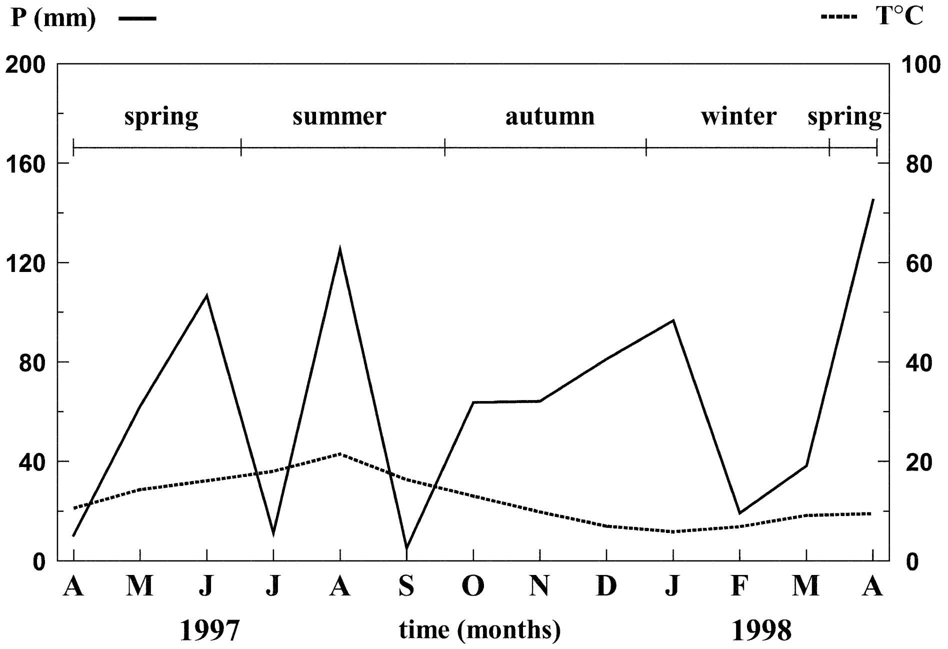

Fig. 1. Diagram showing monthly rainfall and temperature data ($P = 2T$) over the study period. P = total precipitation (mm), T = temperature (°C).

five new inter-rows: two inter-rows compacted by wheel tracks of tractors (soil bulk density of 1.38 g cm^{-3} at 5-cm depth), another two by wheel tracks of a tow full of maize ensilage (soil bulk density of 1.34 g cm^{-3} at 5-cm depth), and the last one no-compacted, i.e. no traffic (soil bulk density of 1.27 g cm^{-3} at 5-cm depth). The differences in soil bulk density between untrafficked and trafficked inter-rows were highly significant, while no difference was observed between inter-rows with wheel tracks or tow passage (Mann–Whitney *U*-test, 95%, $n = 10$, $p = 0.0082$ and $p = 0.0002$, respectively).

After each rainfall event, as quickly as possible, the amount of water collected was noted. Two aliquots of 500 ml were taken after mixing the whole volume in the container and one of them was immediately filtered at 0.45 μm. All samples were kept at 4 °C for less than 24 h before analysis in triplicate. Total P (TP) and total dissolved P (TDP) were determined colorimetrically in crude and filtered extracts, respectively, using the molybdate acid procedure (Murphy and Riley, 1962). Digestion was made by the addition of H_2SO_4, 4 N, and $K_2S_2O_8$ on water samples, which were put in an autoclave at 120 °C for 1 h. The difference between TP and TDP gave the amount of particulate P (PP). Soluble reactive phosphate (SRP) was also measured in filtered extract following the Murphy and Riley method but without digestion.

A runoff coefficient (Rc) was determined as the ratio of the collected volume to the volume of the rainfall precipitation corresponding to the contributive upslope area for each collector. This area ($18.75\ m^2$) was calculated as the upslope length to the collector (25 m) multiplied by the width of the collecting area (0.75 m), corresponding to the space between two maize rows. Sediments collected during the water filtration were dried (40 °C).

According to Cros-Cayot (1996) who worked on runoff in the same study plot, the sample technique tested at the laboratory showed that the sediment load is overestimated especially for water runoff volumes higher than 20 l. So, the correction factor elaborated by this author was used in our study to determine the actual sediment concentration $\mathrm{Csf} = [1.34\mathrm{e}^{(-0.02\ \mathrm{Vr})}] \times \mathrm{Cs}$. Cs is the sediment concentration measured ($g\ l^{-1}$) and Vr (l) the amount of runoff water collected in the container. To determine the sediment concentration and the chemical composition, organic P was determined on sediment by igniting soil sediment samples at 550 °C. After ignition, H_2SO_4, 2 N, was added and the samples were checked during 24 h. Phosphorus was then colorimetrically determined and the difference between ignited and non-ignited samples gave amounts of organic P (Anderson and Ingram, 1993). Organic N, organic C and organic matter contents were analyzed by the INRA laboratories following the AFNOR norms. All data were statistically analyzed using the non-parametric test of Mann–Whitney *U* (Minitab version 12 software).

3. Results

3.1. Runoff events

Parameters of all 42 rainfall events, i.e. amount of precipitation and rainfall intensity, are listed in Table 1. In spring 1997, three rainfall events showed more than 12 mm of precipitation and a minimal intensity of 30 mm h^{-1} (event 7, 11, 13). During summer, two storm events occurred ($P = 25.5$, Imax = 60 mm h^{-1}, and $P = 54$, Imax = 50 mm h^{-1} for rainfall event 19 and 20, respectively). In autumn, after crop harvesting, less intense but more frequent events occurred with two outstanding events, 25 and 26. Winter 1997/1998 and spring 1998 were particularly characterized by successive rainfalls during a few days that were called «rain trains». Four of these rain trains (35, 40, 41 and 42) were prominent. Rainfall event 37 was outstanding for its amount of precipitation (27.5 mm). The volume of runoff waters varied over the different seasons (Table 1). Just after ploughing and sowing, runoff volumes were very small (100–200 ml), despite the high precipitation and the rainfall intensity, while at the end of spring, volumes were more important (55 l for rainfall events 11 and 13). The runoff coefficient Rc was nil at the beginning of maize cultivation but reached 23% and 24% for rainfall events 11 and 13, respectively. In summer, July was water-deficient, but two strong storm events in August (rainfalls 19 and 20) resulted in important water runoff volumes (45–60 l) due to a soil infiltration

Table 1
Rainfall events from April 1997 to April 1998

Rainfall events					Water runoff		Sediments ($g\ m^{-2}$), mean ± SE
Number	Date	Days	Pt (mm)	Imax ($mm\ h^{-1}$)	Volumes (l), mean ± SE	Rc (%), min–max	
Spring							
1	26/04/97	0	9.5	10	0.2 ± 0.1	0–0	0.0
2	4/05/97	9	5.5	10	0.1 ± 0.1	0–0	0.0
3	5/05/97	10	5.5	5	0.0	0–0	0.0
4	9/05/97	14	4.5	25	0.1 ± 0.0	0–0	0.0
5	10/05/97	15	8.5	20	0.1 ± 0.0	0–0	0.0
6	16/05/97	21	6.5	15	0.2 ± 0.1	0–0	0.2 ± 8.7
7	**17/05/97**	**22**	**12.5**	**50**	**1.2 ± 0.7**	**0–1**	**0.2 ± 2.9**
8	18/05/97	23	5.0	10	1.3 ± 0.5	0–3	0.3 ± 0.9
9	19–21/05/97	25	14.0	10	9.4 ± 2.5	1–6	2.3 ± 1.3
10	6/06/97	42	7.0	10	0.2 ± 0.0	0–0	0.0
11	**7–8/06/97**	**43**	**14.0**	**35**	**55.0 ± 5.0**	**13–23**	**37.7 ± 14.8**
12	11/06/97	45	5.0	15	0.1 ± 0.0	0–0	0.0
13	**16/06/97**	**50**	**13.0**	**30**	**55.0 ± 50**	**14–24**	**14.8 ± 2.4**
14	22/06/97	56	17.0	15	1.7 ± 0.4	0–1	0.2 ± 0.4
Summer							
15	25/06/97	59	10.0	5	0.5 ± 0.2	0–1	0.0
16	27/06/97	61	28.0	25	4.1 ± 0.3	1–1	0.2 ± 0.1
17	30/06/97	64	12.5	15	1.4 ± 0.6	0–1	0.0
18	5/08/97	100	19	25	0.9 ± 0.6	0–1	0.0
19	**10/08/97**	**110**	**25.5**	**60**	**45.1 ± 9.1**	**5–12**	**4.7 ± 3.6**
20	**24/08/97**	**114**	**54.0**	**50**	**60.0 ± 0.0**	**6–6**	**39.9 ± 0.2**
21	27/08/97	117	14.0	45	0.9 ± 0.5	0–1	0.0
22	29/08/97	119	10.5	5	0.1 ± 0.1	0–0	0.0
Autumn							
23	8/10/97	160	24.5	10	0.6 ± 0.2	0–0	0.1 ± 6.2
24	14/10/97	166	12.0	10	0.9 ± 0.4	0–1	0.0
25	**20/10/97**	**172**	**19.5**	**35**	**42.5 ± 8.5**	**3–16**	**18.0 ± 0.3**
26	**5/11/97**	**187**	**15.5**	**20**	**27.6 ± 7.2**	**2–16**	**7.4 ± 1.1**
27	**10/11/97**	**192**	**21.5**	**10**	**8.9 ± 3.6**	**1–6**	**0.9 ± 0.2**
28	20/11/97	202	11.5	15	2.1 ± 0.7	0–2	0.4 ± 0.2
29	21/11/97	203	5.5	20	0.4 ± 0.1	0–1	0.0
30	28/11/97	210	9.0	5	0.8 ± 0.2	0–1	0.0
31	**2/12/97**	**214**	**13.5**	**5**	**1.3 ± 0.2**	**0–1**	**0.0**
32	**10/12/97**	**222**	**14.0**	**5**	**1.5 ± 0.6**	**0–1**	**0.2 ± 0.4**
33	**22/12/97**	**234**	**11.5**	**5**	**2.5 ± 0.3**	**1–1**	**0.0**
Winter							
34	**25/12/97**	**237**	**20.0**	**15**	**2.5 ± 0.9**	**0–2**	**0.3 ± 0.6**
35	**26–07/01/98**	**247**	**59.0**	**25**	**33.1 ± 8.6**	**1–5**	**7.2 ± 0.1**
36	13/01/98	256	9.5	10	1.3 ± 0.3	0–1	0.1 ± 0.5
37	18/01/98	**261**	**27.5**	**15**	**23.7 ± 9.4**	**1–11**	**2.1 ± 0.2**

Table 1 (*continued*)

Rainfall events					Water runoff		Sediments ($g\ m^{-2}$), mean ± SE
Number	Date	Days	Pt (mm)	Imax ($mm\ h^{-1}$)	Volumes (l), mean ± SE	Rc (%), min–max	
Winter							
38	21/02/98	294	11.5	10	1.1 ± 0.3	0–1	0.0
39	3/03/98	306	6.0	5	1.4 ± 0.5	0–2	0.1 ± 0.8
40	**7–13/03/98**	**312**	**17.0**	**10**	**2.6 ± 0.6**	**1–1**	**0.1 ± 0.1**
Spring							
41	**2–6/04/98**	**338**	**26.5**	**40**	**5.7 ± 0.7**	**1–2**	**0.2 ± 0.4**
42	**11–15/04/98**	**342**	**37.5**	**10**	**16.7 ± 4.4**	**1–4**	**2.6 ± 5.5**

Pt: total precipitation, Imax: rainfall intensity, Rc: runoff coefficient. Bold fonts indicate rainfall events mentioned in the text.

capacity lower than the rainfall intensities. The Rc values in summer were lower than those in spring season (a maximum of 12% and 6% for rainfall 19 and 20, respectively). Lower amounts of precipitation and weaker rainfall intensity values were associated with runoff in autumn and winter compared to spring. Just before ploughing in spring 1998, two rain trains occurred. Only the second one (42) was characterized by an important run off, despite its lower rainfall intensity (10 mm h^{-1} compared to 40 mm h^{-1} for rain train 41). So, following many successive rainfalls, a cumulative process occurred by increasing amounts of water volumes and sediment transport. Variation between the five replicate inter-rows was very high, especially over rainstorm events (data not shown), but after harvest, there was no significant differences of runoff volumes either between untrafficked inter-rows and wheel tracks or tow passages ($n = 40$ vs. 20, $p = 0.65$ and $p = 0.41$, respectively), nor between wheel tracks and tow passages ($n = 40$, $p = 0.16$).

3.2. Cast dynamics

For 45 days following the sowing of maize, the surface-cast abundance was about nil (Fig. 2). At mid June, a few casts were observed on the soil surface (9 casts m^{-2}), corresponding to the start of earthworm activity. Later in summer, cast numbers decreased and the low numbers on 11 August (23 casts m^{-2}) may be related to the first eroding rainstorm (19, $P = 25.5$ mm and Imax = 60 mm h^{-1}). At the beginning of September (day 133), weaker rainfall events involved soil moisture, thus enhancing casting activity, and number of casts reached 250 m^{-2}. At the same time, maize plants grew from 0.7 m in June to 2.8 m, keeping the soil moisture near the field capacity and permitting the earthworms to be fully active at the end of summer. After crop harvest, earthworm surface casting

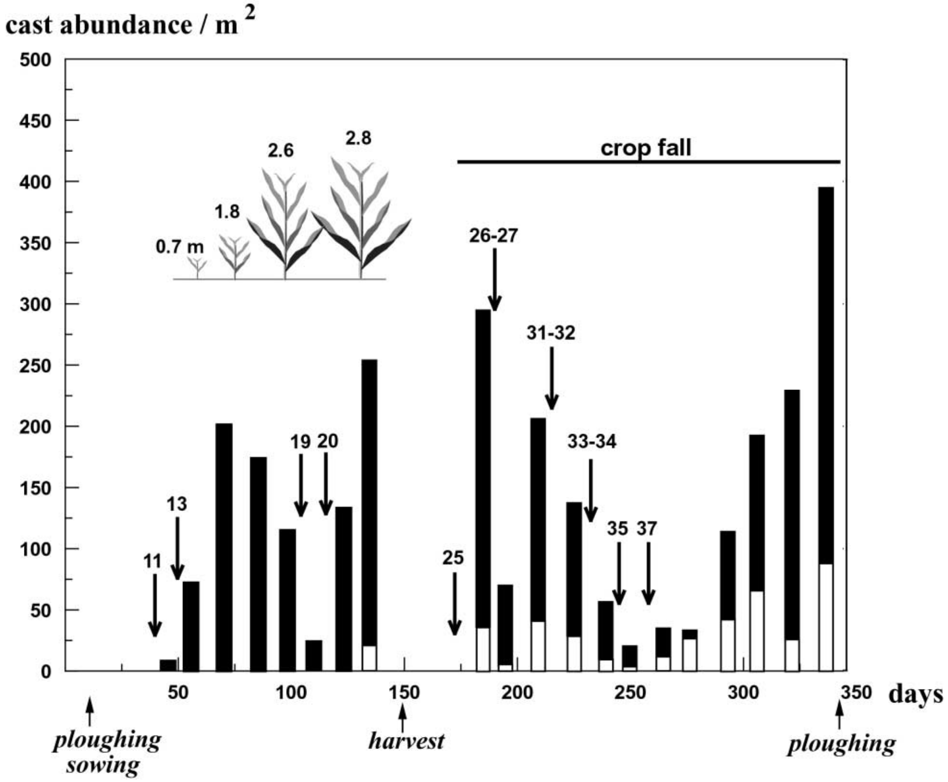

Fig. 2. Abundance of surface casts per square meter on soil surface over the crop related to the main rainfall events. Dark area: ESA species; white area: AN species. The height of maize plants and main rainfall events are specified (see Table 1).

activity was visually absent up to the first days of November (290 casts m^{-2} at day 184). Relationships were emphasized between rainfalls and the decrease of cast abundance (i) after rainfall 26, and especially 27, that happened the day before the cast observation, (ii) after events 31–32 and 33–34 and finally, (iii) after the rain train 35. The decrease in temperatures and also many morning frosts from November to mid-February (day 245 to day 280, data not showed) made earthworm casting activity about nil during this period (between 20 and 35 casts m^{-2}). Cast production increased then from 35 to 400 m^{-2} from mid-February to the next ploughing in April 1998. Over the study year, the ESA casts were the most numerous, while AN casts were observed for the first time just before crop harvest. AN casts only contributed to 10–20% of total casts, corresponding to about 30% of the total mass of casts at the beginning of November (day 184) and 93% at February 1998 (day 280). At the end of the year, the total of minimal cast production was 1328 g m^{-2} $year^{-1}$, while the casts disappearance was at the minimum 765 g m^{-2} $year^{-1}$.

3.3. Soil erosion dynamics

Five different periods regarding soil erosion processes and surface cast dynamics were observed over the year (Fig. 3). At the beginning of the maize growth, just after ploughing and sowing, the soil-surface layer was loose and yet no crust was formed, reducing runoff and enhancing water infiltration. Amounts of water volumes and sediments collected were small (less than 13 l and 3 g m^{-2}, respectively) despite the high intensity of 50 mm h^{-1} for the event 7. Earthworm casting activity was insignificant. At the end of this first period, it was dry for about 2 weeks. The following rains (period 2) leaded to surface runoff and soil erosion (68 and 123 g m^{-2} for events 11 and 13, respectively). Following July, which was water-deficient, heavy rain with surface runoff and sediment transport began (period 3). At this time, sediment losses already reached 70% of the annual losses, and enough casts (113 casts m^{-2}) were present at the soil surface to relate their disappearance to soil erosion. Thus, after rainstorms 19 and 20, the minimal cumulative cast erosion reached 24 casts

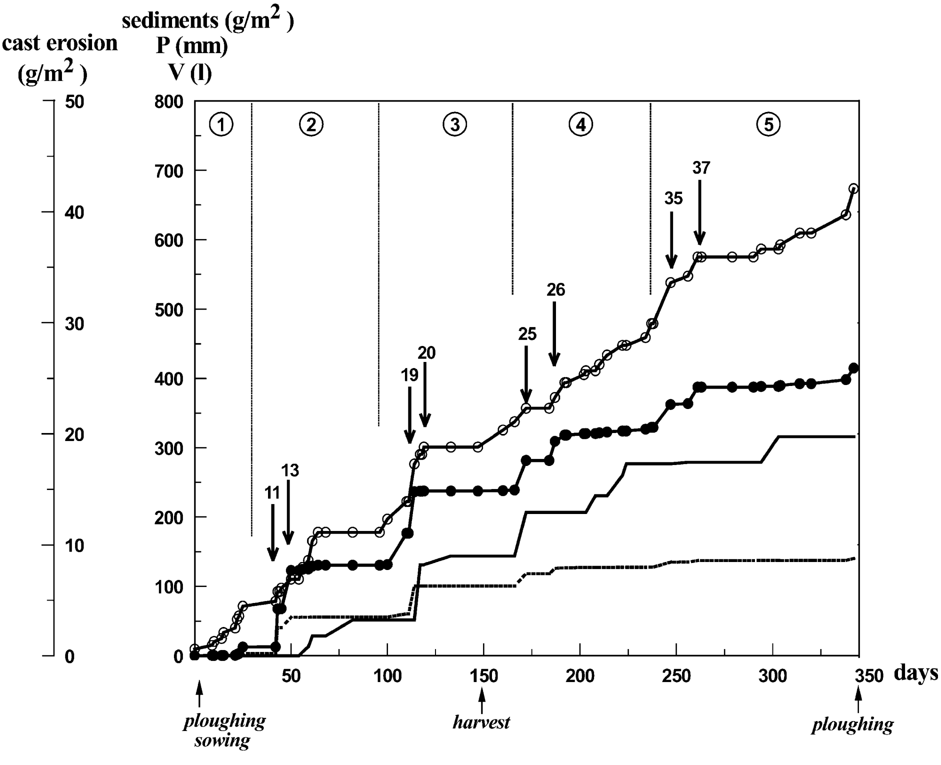

Fig. 3. Cumulative curves of all parameters followed over the year. Line with white points: precipitation (mm); line with black points: volumes of water runoff (l); dotted line: sediment (g m^{-2}); line: minimal cast erosion (g m^{-2}). Main rainfall events are specified (see Table 1).

m^{-2} for ESA species, corresponding to 6.7 g soil m^{-2}. Period 3 ended with a low-rainfall time, and period 4 (after maize harvest) started with enlarged runoff, but without much erosion. ESA surface-casts were more eroded than AN casts (35 vs. 3 casts m^{-2}, respectively). In period 5, rainfall events 35 and 37 caused little soil erosion with less cast contribution.

Over the year, a total of 140.2 g m^{-2} of sediment was eroded. On one hand, sediment transport could be independent from cast erosion over the year, i.e. events 11 and 25 when surface casts were absent on the soil surface. On the other hand, cast erosion and sediment transport are synchronized during two particular periods, i.e. rainstorms in summer (period 3) and rain trains in autumn (period 4).

3.4. Organic matter and phosphorus losses

The organic matter content of the sediments collected in the runoff waters (Table 2) increased significantly (Mann–Whitney *U*-test, 95%, $n = 5$, $p = 0.01$) over the year from 2.54% in spring 1997 (rainfalls 11 and 13) to 4.49% after crop harvest and 5.16% during crop fall in winter (rainfalls 26 and 35). Organic N and C contents progressively increased also, so that the ratio C/N remained unchanged over the study year. Phosphorus losses were closely related to runoff volumes and sediment transport (Fig. 4). Particulate P represented 90% of the total P estimated in samples of water, so the decrease in P losses corresponded to the decrease in sediment transfers. The amount of PP in water decreased progressively during the study period (from 18 to 5 mg of P losses m^{-2}), except a peak in summer due to the rainstorm 20 (24 mg of P losses m^{-2}). Values of soluble reactive P were closely related to the amounts of sediment losses and reached a maximum of 2.14 mg m^{-2} during the rainstorm event 20 in August (data not showed). Over the year, soluble P levels were the following: 1.42, 0.93, 1.17, 1.01, 0.47, 0.46 and 0.24 mg P m^{-2} for rainfall events 11, 13, 19, 25, 26, 35 and 37, respectively. Parallel to the organic matter enrichment, the amount of P in the sediments collected in the runoff waters increased from 1.1

Table 2
Total organic matter, carbon and nitrogen content of sediment collected in runoff waters

Rainfall	OM (%), mean ± SE	Corg (%), mean ± SE	Norg (%), mean ± SE	C/N
11 and 13	2.54 ± 0.57	1.48 ± 0.33	0.18 ± 0.05	8.22
20	2.76 ± 1.29	1.60 ± 0.75	0.19 ± 0.09	8.42
26	4.49 ± 0.23	2.61 ± 0.13	0.34 ± 0.02	7.68
35	5.16 ± 0.31	3.00 ± 0.18	0.37 ± 0.01	8.11

OM: organic matter; Corg: organic carbon; Norg: organic nitrogen.

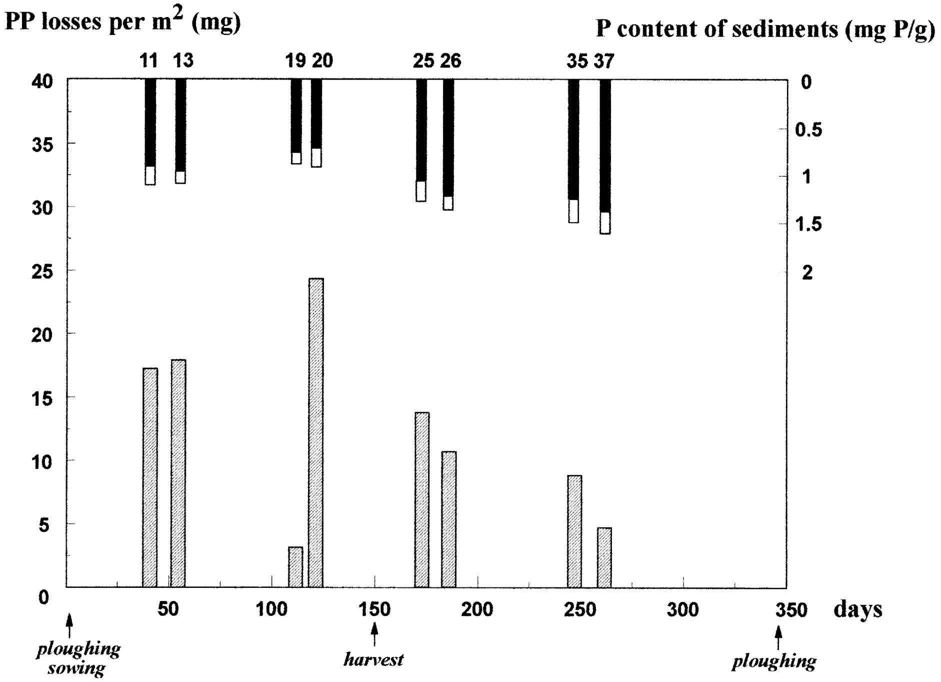

Fig. 4. Particulate phosphorus in runoff waters and phosphorus content of sediment. Black and white areas: inorganic and organic phosphorus, respectively. Main rainfall events are specified (see Table 1).

mg g^{-1} in spring 1997 to 1.6 mg g^{-1} in winter 1997–1998 and inorganic forms represented 80–90%.

In conclusion, over the year, (i) a total of 1328 g m^{-2} $year^{-1}$ of casts (minimum) was produced and 765 g m^{-2} $year^{-1}$ of casts (minimum) disappeared, assessed on a 15-day interval observation, (ii) 140.2 g m^{-2} $year^{-1}$ of sediment were eroded, which corresponded to (iii) losses of 152 mg m^{-2} $year^{-1}$ of total P, and (iv) 21.10 g m^{-2} $year^{-1}$ of organic matter losses.

4. Discussion

It appears that both physical and biological factors influenced the microtopography of the soil surface and, consequently, the water runoff.

After final seedbed preparation of soil on April 1997, no surface runoff occurred. As the soil surface was crust-free, the water flow was governed by the saturated hydraulic conductivity of the soil surface layers, that is usually positively correlated with percolation and negatively with surface runoff (Pitkänen and Nuutinen, 1998). In our study, the sediment losses that began in June (rainfalls 11 and 13) corresponded with the development of a sealing crust that we visually observed (Fig. 5). A large amount of water runoff occurred in summer, despite the protection against the direct impact of rainfall by the vegetation cover (Ellison, 1948) and numerous cracks created consecutive to physical processes as wetting and drying cycles. This result may be partly explained as a consequence from the water deficiency in July that induced a great drying of the soil surface. Runoff occurs more quickly when rainfall intensity was superior to the soil infiltration capacity, as well as with dry soil aggregates than with wet ones in artificial conditions (Le Bissonnais, 1988, 1989).

Concerning biological processes, earthworms, by their burrowing and casting activities cause disturbance of the soil surface microtopography, leading to creation of channels that act as preferential flow paths for water (Bouché and Al-Addan, 1997). While most authors have worked in permanent pasture or at the laboratory, our study is based on the tracking of surface-cast dynamics under a tillage-fallow phase that allowed us to take into account the seasonal activity of earthworms. Anthropic actions, as land-use practices, have often been assumed to affect earthworm mortality and population decline (Lee, 1985; Jordan et al., 1997). In our study, a close synchronization existed between these practice tillage and earthworm activity which was thus interrupted for several weeks (4–5) following both ploughing and crop harvest (Fig. 2). The lack of

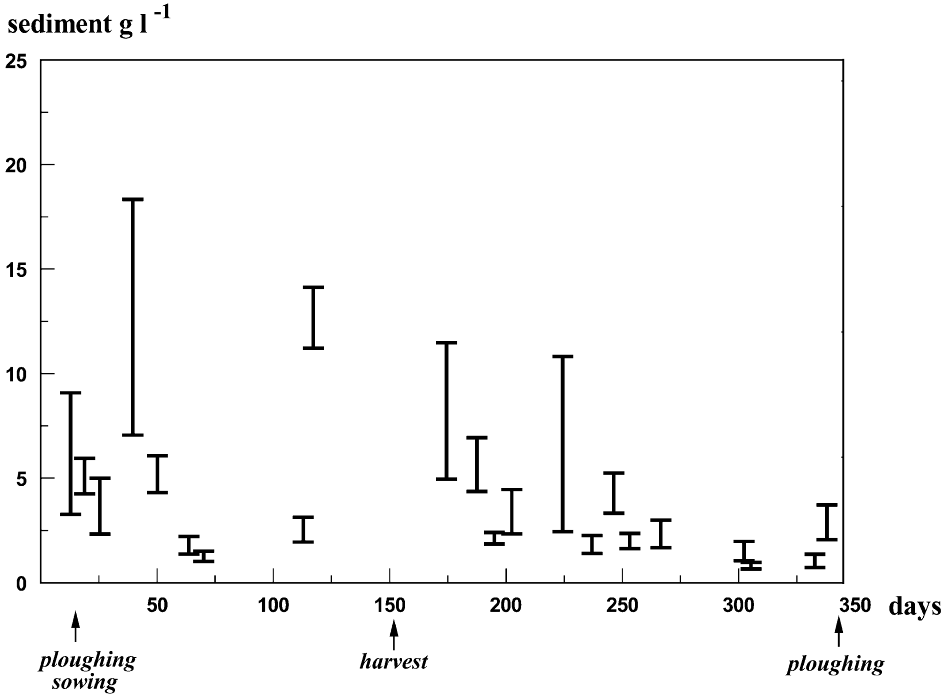

Fig. 5. Load sediment in water runoff over the year (mean ± SE).

AN casts at the beginning of our study may be explained by the ploughing in spring that has affected mainly anecic species by killing adults and/or allowing them escape and retreat deep into the soil. In autumn, after crop harvest, AN casts were observed in the field, which could correspond with both the maturation of juvenile anecic worms and the emergence of the adults to the soil surface as showed by Binet (1993).

Under permanent pastures, Beugnot (1978) and Sharpley and Syers (1977) showed two peaks of activity, one in spring and the other in autumn. In our study, the maize cover kept the soil moisture avoiding quiescence and permitting the earthworms that have no diapause to be fully active in summer. Our annual observations (15-days interval) over 1997–1998 showed that the surface-cast production reached a minimum of 1.3 kg m^{-2} $year^{-1}$. The increase in soil roughness caused by surface-casts may lead to reduced soil erosion by preventing the development of a thin coating of water during rainfall (Siegrist et al.,1998). In contrast, surface-casts may increase soil erosion and particulate transfers if the casts become detached from the soil matrix. This last hypothesis was enforced by the synchronization between the cast disappearance and the increase in sediment transfers for rainstorm events observed in summer (19 and 20), as well as after the rains in autumn (25 and 26). The numerous openings of burrow holes observed after a rainfall event led us to think that surface-casts previously present were eroded and washed away by runoff waters, although Roth and Joschko (1991) suggest that the opening burrows could be made by earthworms after rainfall. In winter, period 5 started with enlarged runoff but without much soil losses. This may be due to the lack of earthworm casts onto the soil surface and low infiltration rate due to compacted wheel tracks. Because of the space-time variability of cast abundance, no systematic relation is outline over the year, but just for defined periods where they were numerous (summer and autumn). A minimum amount of 765 g m^{-2} $year^{-1}$ from casts was lost at the end of the year; that is half from the annual cast erosion of 1.2–1.5 kg (d.w.) m^{-2} $year^{-1}$ extrapolated previously (Le Bayon and Binet, 1999). A better assessment of the contribution of surface-casts to soil erosion dynamics would need closer observations of cast production (e.g. a 2-day interval) on larger sites, but seems very difficult and time-consuming to set up at the field scale.

Studying the nutrient enrichment of runoff waters that showed a high variability between the five inter-rows, an increase in the organic matter and P content of the sediments collected in runoff waters was observed (Fig. 4 and Table 2) while the quantity of soil material eroded decreased (Fig. 5). Earthworm surface-casts could contribute to the release of organic matter and P because of selective ingestion of the finest particles and organic material by earthworms, and the fact that casts were shown to be enriched in water-soluble P (Graff, 1970; Sharpley and Syers, 1976, 1977). As earthworm casts were found to contain a mean of 0.80 mg P g^{-1} (Binet and Le Bayon, 1999), and the present data show a minimal cast production of 1.3 kg m^{-2} $year^{-1}$, a potential amount of 1040 mg P m^{-2} $year^{-1}$ may be relocated with time-lag. However, Sharpley et al. (1979) found that only 3% of the quantity of casts produced annually were transported in surface runoff, which would correspond here to about 20% of the total losses of P. So, most of the cast material could not have reached the collectors during rainfall because (i) it is limited to movement over the course of a few centimeters only, related to the gentle slope of the site (4.5%), and (ii) it is otherwise likely to become mixed into the soil surface matrix.

In conclusion, this study showed that both soil crustability and earthworm activities influenced soil erosion and nutrient transfers under a cultivated plot. Annual observations, even at 15-day intervals, are not sufficient to outline relationships between biological and physical processes. Further experiments based on a simulated rainfall in the field are now needed to know whether casts are entirely transported by runoff waters or only dispersed around their initial position. We will also investigate the different forms of P in surface casts to determine if any are rapidly released to water runoff.

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