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Space-time dynamics in situ of earthworm casts under temperate cultivated soils

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Abstract

Soil does not always benefit from disturbance by earthworms. We investigated whether (under a temperate climate and in maize growing in rows running down-hill) earthworm casts could contribute to soil erosion and losses of nutrients in runoff water. Observations of casts were made in compacted (wheel-tracks) and non-compacted (untrafficked) inter-rows, for a 2-month period in spring. Estimates of surface-cast production in a temperate maize crop ranged between 2.5 to 3.2 kg (d.w soil) m^{-2} y^{-1}. The mean life-time of casts was shown to vary from 4 d during wet periods to 14 d during dry periods. The oldest casts recovered in situ were at least 2-months old. The relative loss of casts was 70% and 20% during the wet and dry periods, respectively. Splash and runoff effects of rainfall were the main causes of deterioration of surface-casts, especially fresh ones. Apart from rainfall events, a prolonged process of erosion took place whereby casts disappeared gradually by collapsing and mixing in the matrix bulk-soil. Cast production was found to be 50% higher in compacted soil. Particularly, an increase by 20% of soil compactness led to a 2-fold increase of casting activity per worm. This suggests that risks of soil erosion could be increased by earthworm surface-casting in compacted soil. Spatial distributions of both casts and earthworms across inter-rows were shown to be similar under non-compacted inter-rows but different in compacted areas. We estimated that annual soil erosion from surface-casts would range from between 1.2 to 1.5 kg (d.w) m^{-2} y^{-1}.

1. Introduction

Soil physical structure is affected by its macrofauna. The bioturbation action induced by earthworms, i.e. their casting and burrowing activities, strongly influences soil structure and porosity (Kretzschmar, 1978; Lee, 1985). For instance, Blanchart (1992) outlined the role of geophageous earthworms in the restoration of the macroaggregate structure of unstructured savanna soils. Under a temperate climate, earthworm casts were found to be much more stable than field macroaggregates of the same size and hence played a role in the structural stability of soils (Marinissen, 1994). Also, earthworms burrows, by increasing soil macroporosity, may be partly responsible for a higher water infiltration rate.

However, earthworm activities do not always benefit the soil system. Under particular conditions, casting by earthworms was found to increase soil erosion. In an undisturbed tropical forest, surface-casting by earthworms contributed to the impoverishment in fine particles of the surface soil where water run-off occurred and led to the formation of coarser sandy soil (Nooren et al., 1995). Studying soil erosion from under a mixed oak–beech forest, Van Hooff (1983) concluded that the worm *Lumbricus terrestris* was mainly responsible for the bare soil surface that would become subject to splash erosion. In grasslands, earthworm casts deposited on the soil surface were found to be a significant potential source of particulate and dissolved P to run-off waters (Sharpley and Syers, 1976).

In maize crop cultivated in rows running down-hill, there were losses of sediments by run-off and caused considerable damage to ditches and gullies and accumulation of muddy run-off (Cros-Cayot, 1996). Because casts are a potential source of particulates in surface run-off, we investigated whether under temperate climate, earthworm casts could contribute to soil

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erosion and losses of nutrients by run-off waters. We studied the production of earthworm surface-casts and its space-time dynamics in situ in relation to climatic conditions (rainfall events) and site heterogeneity (slope and soil compactness).

2. Materials and methods

2.1. Field site

The study was carried out on a silty loam soil at the INRA experimental site at Champeaux, located near Rennes (Brittany, NW France). The climate is a temperate one, with mild temperatures and a high annual rainfall (750 mm y^{-1}). The site has a gentle slope of 4.5%. The study plot had been growing maize with maize rows running downhill. Observations were made in spring following crop harvest. To take into account the surface heterogeneity of the maize field, observations and measurements were made both on non-compacted (untrafficked) and compacted (wheel-tracks) inter-rows. The latter were characterized by an obvious soil concavity.

2.2. Space-time dynamics of casts

To track cast evolution, two inter-rows were investigated: one non-compacted and one compacted. Four observation sites of 2 m in length × 0.75 m in width (this latter corresponding to the space between maize rows) were defined: two at the top and two at the bottom of the two inter-rows. Prior to the first observation, the observation sites were cleared with a soft brush to remove old casts and other soil aggregates from the soil surface. Cast observations were made through a grid set up 5 cm above each observation site by 6 stakes fixed in the soil and that maintained the position of the grid. The grid, 2 × 0.75 m, was composed of 585 elementary square units of 5 × 5 cm, distributed among 15 columns (x) per 39 rows (y). Each square was numbered as (x, y) coordinates and casts were listed according to the square location. Date of appearance and date of disappearance for each cast were recorded to allow calculations of life-time and rate of cast deterioration. Cast morphology related to age was also described on the basis of the physical aspect (as moist, dry or eroded) and the colour (as brown, brown light or whitish).

Rainfall data were gathered during the 2-months of the study. Four rainy periods and two dry periods (without any rain) were defined and particularly examined for cast morphology and cast disappearance to specify further the effects of rainfall on cast deterioration (Table 1). Three rainfall events showed precipitation and intensity which were at least 15 and 5 mm h^{-1}, respectively (22 April, 1 and 6 May, 1996), while the fourth rainfall event was taken into account (18 May) for its considerable intensity of 25 mm h^{-1}. The relative loss of different morphological types of casts were calculated for each period as the ratio between the number of casts that disappeared during the climatic event (rainfall or dryness) and the number of casts present just before the climatic event.

Observations for dynamics of casts were made every day during rain periods and at 3-d intervals on other days for a 2-month period in spring (26 March–29 May 1996). Between recordings, the grid from each observation site was removed to exclude its possible disturbance on rain splash. To assess the slope and soil compactness on cast production, normality and homogeneity of variance of cast samples were tested prior to ANOVA analysis (Minitab, version 8, 1993).

2.3. Earthworm populations

Two weeks before studying casts, earthworms were sampled from under two inter-rows, one compacted and one non-compacted, adjacent to the ones defined for cast observations. The method of Bouché and Alliaga (1986) in which chemical and physical extractions are combined, was used. Three different zones (top, middle and bottom) from along each type of inter-row, i.e. three quadrats of 1 m^2 per inter-row type, were sampled. All worms were weighed and identified to species level. Abundance and biomass (g m^{-2}, on fresh weight basis) both from compacted and

Table 1
Characteristics of rainfall events and dry periods taking into account for cast study. (d: dry period; r: rainfall events; P_t: total of precipitations; I_{max}: rainfall intensity)

Periods	From	To	Time (d)	Date of rainfall event	P_t (mm)	I_{max} (mm h^{-1})
d1	31 March	7 April	8	–	–	–
r1	19 April	23 April	5	22 April	19	15
r2	29 April	2 May	4	1 May	17.5	20
r3	3 May	10 May	8	6 May	15	5
d2	10 May	16 May	7	–	–	–
r4	16 May	20 May	5	18 May	8	25

Table 2
Numbers and biomass of earthworms ($n = 6$, mean ± S.E. and percentage) from the experimental plot in March 1996

Species	Non-compacted inter-row				Compacted inter-row			
	numbers		biomass		numbers		biomass	
	no m^{-2}	%	g m^{-2}	%	no m^{-2}	%	g m^{-2}	%
Lumbricus rubellus	50.7	16.9	17.1	16.2	2.5	1.0	0.5	0.5
L. terrestris	42.0	14.0	59.7	56.8	21.5	8.9	55.9	59.9
Allolobophora chlorotica	24.2	8.1	2.5	2.4	10.9	4.5	1.4	1.5
A. icteria	9.7	3.2	5.5	5.2	12.1	5.0	2.0	4.8
A. rosea	0.0	0.0	0.0	0.0	0.5	0.2	0.1	0.1
Aporectodea caliginosa	172.8	57.7	20.3	19.4	193.0	80.2	30.8	33.2
Total	299.3 ± 67.5	100	105.1 ± 17.6	100	240.5 ± 62.5	100	93.3 ± 13.7	100

non-compacted inter-rows were compared pair-wise using the Mann–Whitney *U*-test.

3. Results

3.1. Earthworm community

The mean density and biomass of earthworm community were 275 individuals m^{-2} and 100 g m^{-2}, respectively. No significant difference was observed between compacted (C) and non-compacted (NC) inter-rows (Mann–Whitney test, 95%, $P = 0.59$ and $P = 0.75$ for density and biomass, respectively), although earthworm abundances were higher in non-compacted inter-rows (Table 2). With regard to diversity, six different species were recorded: *Aporectodea caliginosa*, *Allolobophora chlorotica*, *A. icterica*, *A. rosea*, *Lumbricus terrestris* and *L. rubellus*. The endogeic *A. caliginosa* was the dominant species (57% under NC and 80% under C inter-rows) followed by the anecic *L. terrestris* (14% under NC versus 9% under C). Regarding biomass, *L. terrestris* represented about 60% of the population for both NC and C inter-rows. Individuals of *L. terrestris* were found to be fewer but bigger under compacted soil. The epigeic *L. rubellus* was well represented under NC (16% of the biomass) but was very rare in compacted soil (less than 1%).

3.2. Spatial variability of cast production

Highly significant differences in cast production were found for both the slope and the compactness of the soil (95%, $P = 0.000$). The soil compactness effect was characterized by more casts under compacted inter-rows than non-compacted inter-rows irrespective of the slope location (Fig. 1). However, the differences in cast production between compacted and non-compacted inter-rows were found to be three times higher at the bottom than at the top of inter-rows, that indicated a slope effect. It is likely that this slope effect, i.e. more casts at the bottom than at the top of inter-rows, which was observed at the study plot scale, accounts for a spatial heterogeneity of cast production in the field. In addition to the spatial heterogeneity along the length of inter-row, variability in cast abundance was also present across the width of inter-rows (Fig. 2). From non-compacted inter-rows, cast numbers were lower in the centre and increased progressively towards the maize row. This specific spatial distribution of casts was not found in the compacted inter-rows from which the numbers of casts were approximately unchanged cross-over the width of the maize inter-row.

3.3. Production and temporal evolution of casts

A total of 5805 casts were counted from 26 March to 29 May, representing an average daily production

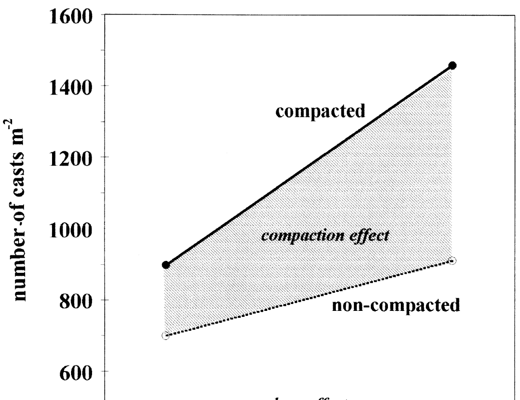

Fig. 1. Site slope and soil compactness effects on cast production during the 2-month period (ANOVA, $^{***}P = 0.000$, 95%).

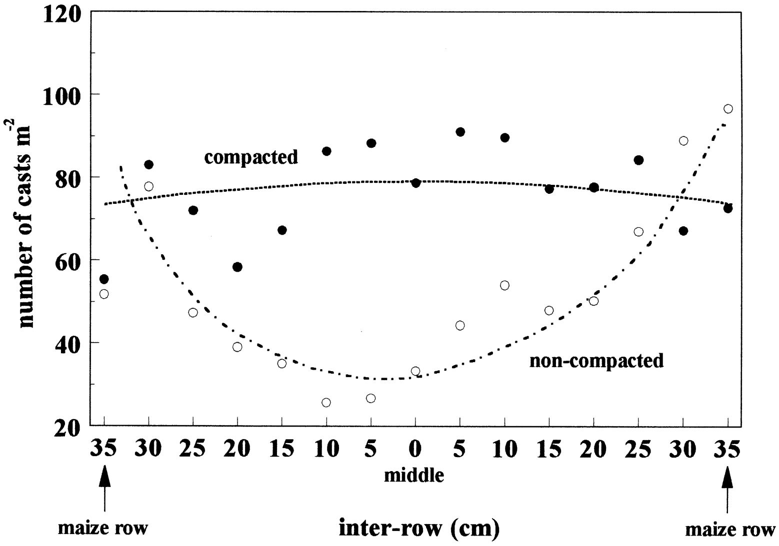

Fig. 2. Spatial distribution of casts across two maize rows in compacted (●) and non-compacted (○) inter-rows.

of 15 casts m^{-2}, i.e. 8.6 g m^{-2} on dry weight basis. Variations in cast production were observed throughout the 2-months (Fig. 3). Some production peaks were found to be higher than 40 casts m^{-2} reaching to a maximum of 80 casts m^{-2} on 10 May. Temporal evolution of cast abundance in situ was calculated by the difference between gross production and disappearance of casts between observations (Fig. 4). Cast abundance increased from 26 March (52 m^{-2}) to a maximum in 18 April (200 m^{-2}), then decreased slowly before falling on the 1 May to the similar low value (54 m^{-2}) recorded at the end of March. Numbers of casts increased again from 6 May, reaching an another peak by the end of May (150 casts m^{-2}). More important however were the obvious relationships found between cast disintegration and rainfall events, cast number decreasing after each important rainfall event. In particular, a significant effect on cast disappearance was observed when precipitation and intensity of the rainfall event were at least 15 and 5 mm h^{-1}, respectively.

3.4. Age groups and life-time of casts

During a 65 d observation, the oldest casts were found to be 57 d old. The age groups distribution was similar for both compacted and non-compacted inter-rows, i.e. cast numbers decreased with ageing groups. However, the large difference in cast numbers between the 5–10 d old group and the 10–15 d old group suggested a 10-d old threshold beyond which the rate of cast disappearance slowed down (Fig. 5). In fact,

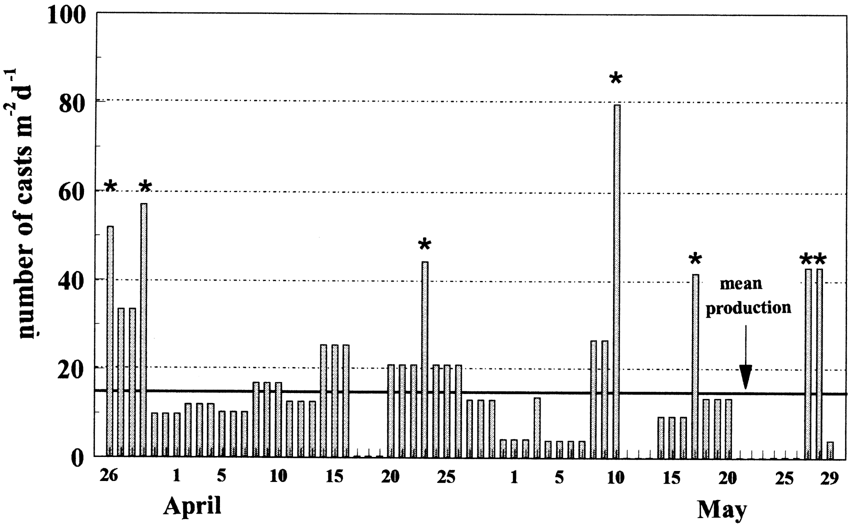

Fig. 3. Daily production of surface-casts per square meter over the study period (the line indicates the mean production; *: production peak).

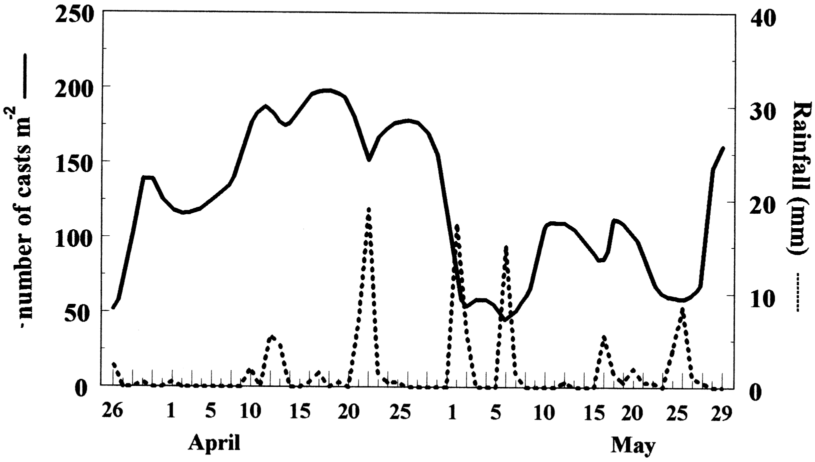

Fig. 4. Temporal evolution of cast abundance relative to rainfall events.

calculations of the slope of each straight line showed that casts disappeared at least at half the rate, once they were 10 d old, compared to younger casts (slope of −134 and −61.5, respectively). The duration of casts was shown to be related to climatic conditions on the day they appeared. The mean life-time of casts was calculated to be 11, 7 and about 4 d for a dry period (26 March to 7 April), a drizzly period (10 April to 16 April) and a wet period (19 April to 7 May), respectively (Fig. 6). Casts appearing after 7 May were excluded from the analysis because decay-rates and cast collapse remained unknown once the experiment had stopped. Maximal longevity was also 3 to 4 times longer for casts appearing in March (dry period) than for those produced at the beginning of May (wet period). Inversely, the minimal longevity was constant ranging from 1 to 2 d.

3.5. *Morphological evolution of casts*

To relate morphology to age, three visual morphological types of casts were defined: (i) moist and brown type (MB), i.e. casts were bright and soft to the touch and had a fresh aspect, (ii) dry and whitish type (DW), casts were light brown to whitish and were hard to the touch, (iii) eroded type (ER), casts had fuzzy features and most often casts were moss-covered or colonized by white fungi. For the age group of 0–5 d old, MB casts, i.e. fresh casts, occurred abundantly (Fig. 7). The relative abundance of MB casts, DW casts and eroded casts were of 90, 8 and 2% at d 1, respectively. Fresh casts decreased quickly becoming in the minority at 10–15 d old (30%) and disappeared within the month. After 30 d old, only dry and eroded casts remained on the soil. In the oldest age group of 40–60

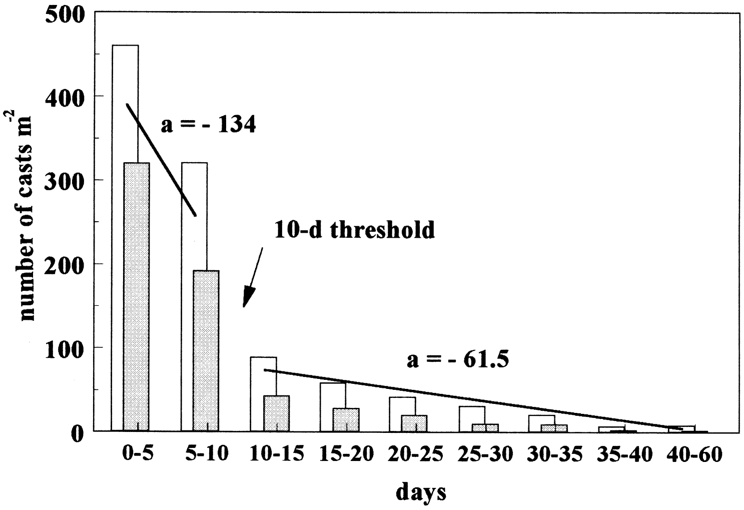

Fig. 5. Importance of the age-group of casts in compacted (white area) and non-compacted (shaded area) inter-rows from 26 March to 29 May 1996 (*a*: slope). A 10-d threshold beyond which casts disappearance collapsed is shown.

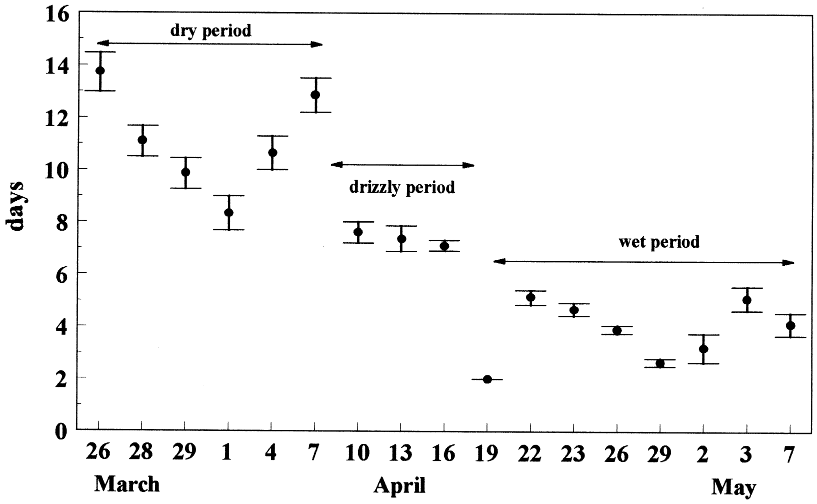

Fig. 6. Life-time of earthworm casts in relation to climatic conditions of the date they appeared (mean ± S.E.).

d, eroded casts were dominant (70%). So a gradual deterioration of cast morphology, i.e. initiating from a fresh appearance followed by a dry and flat one and ending by an eroded morphology, accounts for an ageing process of earthworm casts that could occur on a long-range time scale for about 20% of cast populations.

3.6. Relationships between cast morphology, cast disappearance and rainfall events

The rate of cast disappearance was about 3.5-fold faster during wet periods than dry periods, i.e. 70% versus 20% of casts, respectively (Fig. 8). Most of the casts that disappeared during each dry period were fresh ones (93.1 and 93.2% for d1 and d2, respectively). The difference between rainfall effects could be noted regarding the morphology of casts that disappeared. Over the train of rainfall, that was formed by three successive rainfall events (r1, r2 and r3) within 17 d, the relative disappearance of casts increased from 62.4 to 72.1%. Most of the casts disappearing during r1 were dry (67%). Inversely, fresh casts were mainly removed during r2 and r3 (78 and 59%, respectively). A significant deterioration (25%) of older casts was only observed for r1 and r3. The fourth rainfall led also to an important rate of deterioration (68%) which was similar to the one obtained at the end of the period of rainfall. This effect was probably related to the high intensity of this rainfall event.

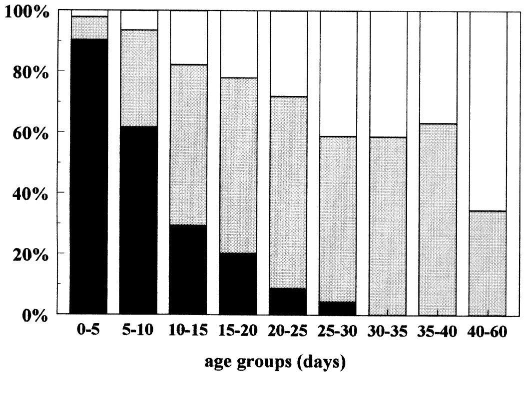

Fig. 7. Cast morphology relative to age (dark area, MB: moist and brown; shaded area, DW: dry and whitish; white area, ER: eroded aspect).

4. Discussion

4.1. Earthworm community and spatial distribution of casts

The earthworm community in the plot investigated was considerable as long as the plot was cultivated under conventional-tillage for maize crop. Compared with a previous study conducted in spring on a maize crop fertilized with farmyard-manure nearby our study plot (Binet, 1993) earthworm density was similar (275 versus 258 ind m^{-2}) while biomass was twice as high (100 versus 47 g m^{-2}). Abundances, especially biomass, were in the range of those obtained under an integrated-tillage plot in Netherlands (400 ind m^{-2} and 100 g m^{-2}) by Marinissen (1992). Residual litter of maize plants upon the soil surface, by providing a continuous food supply for the worms over the winter period, could explain (i) the high worm biomass observed and (ii) the significant presence of both the epigeic *L. rubellus* and the large anecic *L. terrestris* (60% of the biomass community). In compacted areas, individuals of *L. terrestris* were fewer but bigger while individuals of *L. rubellus* were almost absent. This out-

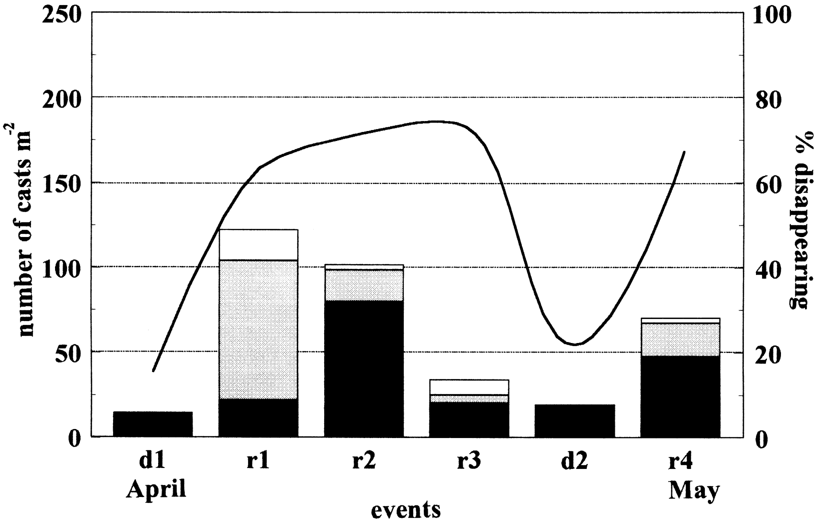

Fig. 8. Gross (histogram) and relative (line) disappearing of casts in relation to rainfall events. (dark area, MB: moist and brown; shaded area, DW: dry and whitish; white area, ER: eroded aspect). (see Table 1 for specifications of events).

lines a spatial discrimination among earthworm species due to soil compactness.

Earthworms were found to be 20% less numerous in the compacted inter-rows, although the difference was not significant. Bulk-density, previously measured in the same plot under non-compacted and compacted inter-rows, were found to be of 1.25 and 1.50 g cm^{-3}, respectively (Heddadj et al., 1996). So, our results support the negative correlation between soil compactness and earthworm density shown by Binet et al. (1997). Inversely, cast production was increased (+50%) in compacted inter-rows. This is probably related to the fact that, in compacted soils where macroporosity is low, earthworms cannot move forward by pushing the soil matrix aside but they have to eat their way through the soil and throw out soil onto the surface, as it was shown by Dexter (1978). Calculations from our results demonstrated that an increase of the soil compactness by 20% led to an individual casting activity two times greater: 2.9 versus 1.5 g d.w of cast per worm, under compacted and non-compacted soils, respectively.

The soil compactness induced also an heterogeneity in the spatial distribution of worm casts that was observed both from along the length and across the width of the maize inter-rows. Under non-compacted inter-rows, we showed that spatial distribution of casts across two maize rows paralleled the spatial distribution of earthworms previously observed by Binet et al. (1997), i.e. casts as earthworms are primarily located along the maize row than in the centre of the inter-row, their abundances decreasing with distance from maize row. In contrast, the spatial patterns of both casts and earthworms differed in compacted areas, cast number being completely unchanged across the width of the inter-rows. In the centre of the compacted inter-rows, there were probably less earthworms than along the row because of the higher soil bulk-density at this location (Binet et al., 1997). But at the same time, as we calculated above, the individual casting activity per worm might have been greater too. So, this probably explains why cast production in the centre of the compacted inter-row equalled the one along the row where earthworms are concentrated.

Because cast production as well as water run-off (results not shown) are higher in compacted inter-rows, erosion and disintegration of surface-casts would be more important in compacted area.

4.2. Time dynamics of cast production

Our analysis of casts, on a daily basis, showed that production was irregular and consisted of peaks of production. Except the first two, all these peaks appeared within 1 to 3 d (depending on the previous weather) following an important rainfall event. This points out that earthworm activity and particularly surface-cast productions is subordinate to soil moisture and is in line with previous observations from tropical ecosystems reported by Nooren et al. (1995). A greater production of casts was observed at the beginning of the study during a dry period which must be considered as a bias in the experiment, due to the clearing-up of the area prior to observations. In response to the disturbance, earthworms produced numerous casts to once again block their burrow holes. In addition, the deficit of food supplies created by the removal of maize litter probably led earthworms to burrow more through the soil to provide for their needs. A similar behaviour was also suggested by

Martin (1982). The mean production observed in our study (8.6 g m^{-2} d^{-1} on dry weight basis) was (i) of the same order as the maximum observed at the end of the rain season under a grassy-savanna of 12.5 g (d.w) m^{-2} d^{-1} (Blanchart, 1990) but (ii) only one-eighth (70.5 g (d.w) m^{-2} d^{-1}) of the cast production under temperate pasture (Graff, 1971 in Lee, 1985). Because the spring in 1996 was exceptionally dry, it is likely that our mean production for spring was underestimated. According to Beugnot (Dijon, 1978, unpublished report), under a temperate climate, spring showed a high casting activity which may be 50% greater in the fall; during winter, casting-activity is half reduced compared to the spring while it could be considered as nil over the summer. Assuming this model, estimates of annual production in temperate maize crop would range between 2.5 to 3.2 kg (d.w) m^{-2} y^{-1}. Although cast production was important in the wet months, abundance of casts in the field was lower than in drier months. Because cast density depends both on production process and disintegration process, this pointed out an obvious effect of rainfall events on cast-collapse. However, both the rapid disappearance of some newly-formed casts and the survival in the field of aged casts account for two modalities in cast deterioration, i.e a fast and a slow one, that interact together. Rainfall was the main cause of the fast process of cast disintegration that worked in two ways: its 'splash' effect, i.e. the kinetics of the drops, broke down casts while its 'run-off' effect removed-up and transferred soil particles. According to Ellison (1944 in Cros-Cayot 1996) who firstly studied the rainfall effect on the deterioration of soil aggregates and Cros-Cayot (1996), this type of erosion was defined as 'diffuse'. On the other hand, during calm-weather periods, a long-time scale process of erosion took place whereby cast disappeared progressively by collapsing and mixing with the matrix bulk-soil. Visually, this slow process of cast deterioration generated a gradual passage from fresh, dry and finally eroded, aspect of casts. No water transfers of soil particles occurred in this latter case. Although no data were recorded, high air moisture during foggy weather as well as wind probably played a part in this gradual erosion.

4.3. Age-hardening and life-time of casts related to rainfall events

The life-time of casts was shown to be related to the climatic conditions of the day they appeared. It varied from 4 d during wet periods to 14 d during dry periods. It is likely that the initial low stability of newly-deposited casts (Shipitalo and Protz, 1989), especially those with high water content, combined with the moistening effect favored cast-disintegration over a wet period. On the contrary, a calm-period of weather without much rainfall is favorable for the stabilization of earthworms casts during the first few days. The stabilizing process within casts could be related to (i) the decrease of the cast water content that led to the increased linkages between soil particles (Molope et al., 1985; Marinissen and Dexter, 1990) and (ii) the colonization of casts by fungi (Parle, 1963; Tisdall and Oades, 1982) or by moss as we observed in this study. Both stabilizing phenomena might have been at the origin of the critical 10-d old threshold, that we outlined, below which casts disappeared quickly and beyond which cast disappearance slowed down. During the dry period, more casts passed over the critical 10-d and became stable enough to survive the next rainfall events. Actually, irrespective of the pre-existing cast populations, the effects of the rainfall event was found to influence the nature of the casts removed during rainfall events. Thus, the stronger the event (intensity and precipitation), the more old stable casts (dry and eroded) disappeared. It could be also shown that over a train rain, cast disappearance increased exponentially suggesting a cumulative effect of each rainfall event.

From our data, the annual rate of cast disappearance could be estimated to be 52%. Assuming (i) that the latter estimate is relevant and (ii) that the casts that had disappeared were really eroded and transported, annual soil erosion from casts would range between 1.2 to 1.5 kg (d.w) m^{-2} y^{-1}. In terms of soil thickness, this would correspond to a 1.5 mm soil layer that is supposed to be removed and to contribute to the diffuse soil erosion. As a consequence of the selective feeding of earthworms, casts are biological aggregates with high contents of nutrient N and P. Because newly-formed casts could be easily destroyed by rain, it is likely that a discharge of nutrients and soil particles occurred in the water run-off. Analysis of water run-off are needed to confirm this. On the other hand, some casts can acquire high stability with time leading to a long life-time in situ. Thus, earthworm surface-casts constitute also a pool of nutrients whose reallocation might be held over time.

In conclusion, we pointed out in our study that earthworms by their casting activity could have a possible influence on run-off phenomenon and soil erosion, especially from compacted soils. The weather before the rainfall event was found to be as important as the rain intensity and the amount of precipitation in the cast-falling. All these components interact together and make it difficult to define which aspect is preponderant. Further experiments in situ based on the comparison of cast dynamics from a non-protected and protected area against rainfall need to be developed to solve this problem.

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