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ORIGINAL PAPER

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Organic resources and earthworms affect phosphorus availability to sorghum after phosphate rock addition in semi-arid West Africa

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Abstract A field experiment was laid out in Burkina Faso (West Africa) on an Eutric Cambisol to investigate the interaction of organic resource quality and phosphate rock on crop yield and to assess the contribution of earthworms (*Millsonia inermis* Michaelsen) to P availability after phosphate rock application. Organic resources of different quality were applied at a dose equivalent to 40 kg N ha^{-1} with or without phosphate rock from Kodjari (Burkina Faso) at a dose equivalent to 25 kg P ha^{-1}, and were compared with control and single phosphate rock treatments in a factorial complete block design with four replicates. Sorghum (*Sorghum bicolor* L. Moench) variety SARIASSO 14 was grown. Sheep dung had the highest impact on earthworm casting intensity followed by maize straw. Combining organic resources with phosphate rock reduced earthworm casting activities compared to a single application of organic resources or phosphate rock. Addition of phosphate rock to maize straw reduced P availability in earthworm casts whereas combining sheep dung or compost with phosphate rock increased P availability. The contribution of earthworms to Kodjari phosphate rock solubilisation mainly occurred through their casts, as the available P content of casts was 4 times higher than that of the surrounding soil.

Keywords Earthworms · Organic resource · Phosphorus · Phosphate rock · West Africa

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Introduction

In high-input agricultural systems, the importance of soil organisms has often been disregarded, as physical manipulation of the soil, disease and pest suppression, and nutrient supply have been increasingly provided by human inputs rather than by natural processes. Soil organisms regulate important processes such as decomposition of organic matter, nutrient cycling, bioturbation and suppression of soil-borne diseases and pests (Brussaard et al. 1997). Recent research demonstrates that practices which eliminate beneficial soil fauna communities are unlikely to be sustainable in the long term, especially in low-input systems based on organic fertilisation (Lavelle et al. 1994; Mando and Stroosnijder 1999; Wardle et al. 1999).

Earthworms and termites are most important faunal components in soil because they act as ecosystem engineers and have lasting beneficial effects on other species such as decomposers, by modulating soil physical and chemical properties and affecting biological processes such as organic matter mineralisation (Beare et al. 1997; Bonkowski and Schaefer 1997; Curry and Byrne 1997; Fragoso et al. 1997; Marinissen and Hillenaar 1997; Hendrix et al. 1998; Van Vliet et al. 1998; Blanchart et al. 1999).

P is one of the most limiting nutrients in the semi-arid zones. Compared to chemical P fertilisers, phosphate rock is locally available and cheaper but its slow reactivity (as substantial effects are sometimes not seen during the first year of application) and the dusty character of the finely ground material (blowing away effects) are constraints to its adoption by farmers (Chien and Hammond 1989; Gerner and Mokwunye 1995). Mowo (2000) showed that the reactivity of phosphate rock in the soil depends mainly on the calcium carbonate content of the rock.

One-third of soils in southern Burkina Faso are Eutric Cambisols and their neutral pH reduces the agronomic effectiveness of the phosphate rock, because the increasing amounts of dissolving calcium carbonate reduce the dissolution of calcium phosphate (Mowo 2000). How organic resources and soil fauna may interact and influence P availability to crops after phosphate rock addition is poorly understood in semi-arid West Africa.

The aims of the present study were to assess how earthworms can contribute to P availability after phosphate rock addition on Eutric Cambisols and to investigate the combined impact of organic resources of different qualities and phosphate rock on crop performance. We hypothesised that combining organic resources and phosphate rock would benefit crop production. We also hypothesised that earthworm contribution to P availability after phosphate rock addition would be most pronounced in the presence of easily decomposable organic material.

Materials and methods

Site description

The study was conducted in 2000 in Kaibo (11–12°N) in southern Burkina Faso characterised by a north Sudanian climate. The annual rainfall ranges from 750 to 1,000 mm with a mean temperature of 28°C. The rainy season is from June to September with an average rainfall of 935 mm for the last 47 years. Leptosols, Vertisols, Fluvisols, Regosols, Luvisols, Lixisols and Cambisols are the most dominant soil types (BUNASOL 1989; Mulders and Zerbo 1997).

The experiment was laid out on a Eutric Cambisol with a loamy texture (47% sand, 36% silt, 17% clay) in a site previously under fallow for 6 years. The topsoil (0–10 cm) had the following properties: pH (H_2O) 7; pH (KCl) 5.3; 8.3 g organic C kg^{-1}; 0.49 g total N kg^{-1}; 169 mg total P kg^{-1}; 565 mg total K kg^{-1}; 200 mg exchangeable Ca kg^{-1}; 30 mg exchangeable Mg kg^{-1}; 7.8 mg exchangeable K kg^{-1}; 0.23 mg exchangeable Na kg^{-1}. Nutrient depletion and water erosion are the main land degradation problems.

Experimental design and crop and soil management

The experimental design was a factorial complete block design with single or combined applications of organic resource and phosphate rock and a control with four replicates. The size of each plot was 10×10 m. The blocks were separated by 5-m-wide alleys and the plots by 2.5-m-wide guard rows. Organic resources of contrasting quality, maize straw (S), sheep dung (SD) and compost (CO), were applied at a dose equivalent to 40 kg N ha^{-1}. The chemical properties of the organic resources, including their C and nutrient content, are shown in Table 1. Kodjari (Burkina Faso) phosphate rock was applied at a dose equivalent to 25 kg P ha^{-1}.

Table 1 Chemical properties of organic materials applied in 2000 at Kaibo, Burkina Faso

Organic resources	Maize straw	Compost	Sheep dung
Total quantity (kg ha^{-1})	5,195	4,819	2,614
Organic C (kg ha^{-1})	2,343	415	659
Total N (kg ha^{-1})	40.0	40.0	40.0
Total P (kg ha^{-1})	9.4	8.7	8.6
Total K (kg ha^{-1})	62.3	35.0	31.4
Lignin (L) (%)	0.16	0.91	0.16
C:N ratio	59	10.0	17
L:N ratio	0.21	1.10	0.10

All plots were tilled manually by hoeing (3–5 cm) in order to minimise soil disturbance that can affect the activities of soil fauna. Sorghum (*Sorghum bicolor* L. Moench) variety SARIASO14 was used as plant material and sown at the rate of 31,250 seedlings ha^{-1}. During the growing season, the field was weeded twice using hoes. The crop was harvested 4 months after sowing.

Sampling and analysis

Earthworm casts were counted at the soil surface and collected daily from one microplot of 2 m^2 in each replicate positioned in the middle of the plot and thus a total of 32 microplots were investigated. The counting and sampling was done early in the morning before 11 h. After collection, the casts were air-dried and weighed on an electronic balance. Two composite cast samples from each plot were chemically analysed. The first sample was collected 2 months after sowing (flowering) and the second sample before harvest.

Soil samples (0–10 cm) were also collected 2 months after sowing and at harvest. N was measured by colorimetry after sample digestion (Kjeldhal) (Houba et al. 1989). Available P was measured as Bray P as reported by Houba et al. (1989). Rainfall was recorded using a rain gauge placed in the field. The data were subjected to ANOVA.

Results

Earthworm casting activity and cast nutrient content

Earthworm casting intensity and cast weight

Table 2 indicates the impact of the treatments on earthworm casting intensity, cast weight and cast nutrient content. Earthworm casts were most abundant when SD only was added with a general trend in the data showing that phosphate rock reduced the abundance of casts.

Casting intensity varied with time. It was in general higher in the early stage following organic material application than at harvest (Fig. 1). Up to 74 Mg ha^{-1} soil was cast by earthworms onto the soil surface (in SD). The amount of casts (weight) was higher in SD than all other

Table 2 Earthworm cast production and cast nutrient contents in 2000 at Kaibo, Burkina Faso. Data followed by the *same letter* within a column are not significantly different at $P<0.05$. *S* Maize straw, *S+RP* maize straw+phosphate rock, *SD* sheep dung, *SD+RP* sheep dung+phosphate rock, *CO* compost, *CO+RP* compost+phosphate rock, *C* control, *RP* phosphate rock

Treatments	Total cast number (m^{-2})	Total cast weight (Mg ha^{-1})	Total N content (kg ha^{-1})	Total P content (kg ha^{-1})	Total K content (kg ha^{-1})
S	557 ab	49 a	43 b	11 b	34 c
S+RP	395 a	27 a	19 a	6 a	13 a
SD	718 b	74 b	63 c	16 b	46 c
SD+RP	437 a	47 a	35 b	12 b	27 b
CO	376 a	41 a	36 b	11 b	23 b
CO+RP	364 a	34 a	30 b	8 b	26 b
C	431 a	38 a	33 b	9 b	28 b
RP	388 a	42 a	37 b	12 b	28 b

treatments (Table 2). Organic resource quality, sampling period and the interactions between organic resource, sampling period and phosphate rock affected earthworm cast number. Cast weight was affected by the quality of organic resource and the sampling period (Table 3). Cast number and cast weight were in general proportional except in the S+RP treatment where cast weight was much lower in relation to the number of casts recorded.

Nutrient contents in earthworm casts

Table 2 shows nutrient levels in the earthworm casts. The SD treatment showed the highest N, P and K contents in earthworm casts of all the treatments, whereas the lowest N and K contents were observed in the S+RP treatment.

P availability

Total P was always significantly higher in earthworm casts than in soil (Fig. 2). Two months after sowing, single organic resource applications did not affect soil total P content compared to the control (Fig. 2a). Total P was higher in CO+RP and RP than in the other treatments. Cast total P was highest in CO and RP and was lowest in S, SD and the control.

At harvest, soil total P was significantly higher in SD+RP compared with the other treatments. Cast total P did not differ significantly between the treatments (Fig. 2b). Organic resource and phosphate rock interacted in their effects on cast P content. Phosphate rock application and the sampling period affected soil P content but did not affect cast P content (Table 3).

Available P content was always 3–4 times higher in earthworm casts than in surrounding soil (Fig. 3). Two months after sowing, soil available P was higher in CO+RP than in the other treatments (Fig. 3a). Cast available P was significantly higher in CO+RP than in the other treatments with the exception of SD and SD+RP.

At harvest, soil available P content was higher in SD+RP than in the other treatments (Fig. 3b). Available P content of earthworm casts was higher in SD+RP and CO+RP than in the other treatments with the exception of S and SD. Earthworm cast available P did not differ significantly between the single applications of different organic resources.

Two months after sowing and at harvest, cast available P increased significantly after phosphate rock addition to compost. Phosphate rock and organic resources interacted significantly in their effects on soil P availability. Earthworm cast available P was affected by the sampling period (Table 3). Organic resource and phosphate rock also interacted significantly in their effects on cast available P.

The fraction of available P (FAP) expressed as a percentage of total P content in earthworm casts and in surrounding soil was 2–4 times higher in earthworm casts than in surrounding soil. The percentage of total P as available P (Bray) ranged from 1.9 to 2.5% in soil, from 4.1 to 6.5% in casts 2 months after sowing, and from 2.34 to 4.0% in soil, and from 3.9 to 6.4% in casts at harvest.

Two months after sowing FAP did not differ significantly among the treatments. FAP in earthworm casts was highest in CO+RP but did not differ significantly from S, SD, SD+RP and the control. FAP decreased significantly with the addition of phosphate rock in S and the control treatments whereas it increased significantly with the addition of phosphate rock to CO. At harvest, FAP in soil was higher in SD+RP compared with the other treatments. In earthworm casts, it followed a similar trend to that observed at 2 months after sowing.

N content in earthworm casts and in surrounding soil

Figure 4 shows the N content of earthworm casts and surrounding soil. Two months after sowing, soil N content was significantly higher in CO+RP compared to the other treatments with the exception of RP and the control. Cast N content was significantly lower in S+RP and SD+RP compared to the other treatments but it did not differ from

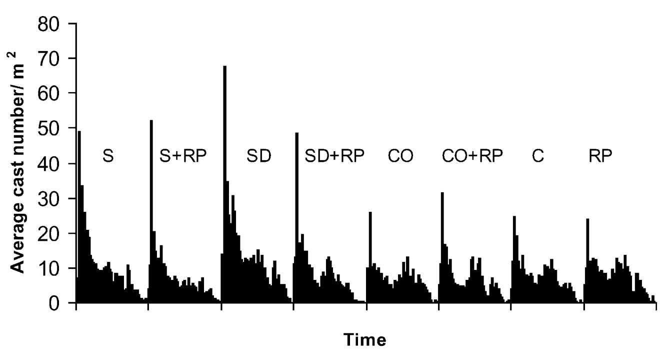

Fig. 1 Effect of organic resources and phosphate rock application to a Cambisol at Kaibo, Burkina Faso in 2000 on the average number of earthworm casts during 4 months after application. *S* Maize straw, *S+RP* maize straw+phosphate rock, *SD* sheep dung, *SD+RP* sheep dung+phosphate rock, *CO* compost, *CO+RP* compost+phosphate rock, *C* control, *RP* phosphate rock

Table 3 ANOVA of earthworm cast production, soil and cast chemical properties and crop performance

Source of variation	Cast number	Cast weight	Soil P (Bray)	Cast P (Bray)	Soil N content	Cast N content	Soil P content	Cast P content	Grain yield	Straw yield
Organic resource	**	*	NS	NS	NS	NS	NS	NS	NS	*
Rock P	NS	NS	*	NS	*	*	**	NS	NS	NS
Sampling period (Period)	***	**	NS	**	NS	NS	***	NS	–	–
Organic resource×rock P	NS	NS	*	*	NS	NS	NS	*	*	NS
Organic resource×Period	*	NS	*	NS	NS	NS	*	NS	–	–
Phosphate rock×Period	NS	NS	NS	NS	NS	NS	NS	NS	–	–
Organic resource×phosphate rock×Period	*	NS	NS	NS	NS	NS	NS	NS	–	–

*P<0.05, **P<0.01, ***P<0.001, *NS* P>0.05

that of RP and the control. No significant difference was observed among the other treatments (Fig. 4a).

At harvest, soil total N content was significantly lower in S and CO+RP compared with the control, RP and SD (Fig. 4b). No significant differences in soil N content were observed between CO+RP, SD+RP and S+RP. Cast total N content was lowest in S+RP and significantly different from the other treatments with the exception of SD and SD+RP. No significant differences in cast N content were observed with the single application of organic resources. The addition of phosphate rock reduced cast N content in the presence of S.

Total N content in earthworm casts and in surrounding soil was significantly affected by phosphate rock application (Table 3). Sampling period did not significantly affect total N content in earthworm casts and in surrounding soil.

Crop yield

Table 4 indicates that RP increased sorghum grain yield in the presence of S. Straw yield was significantly higher in CO+RP compared to most other treatments (except SD+ RP).

Harvest index (grain yield /straw yield) was significantly higher in the S+RP treatment compared with other treatments (Table 4). The lowest harvest indices were observed in CO+RP and SD+RP.

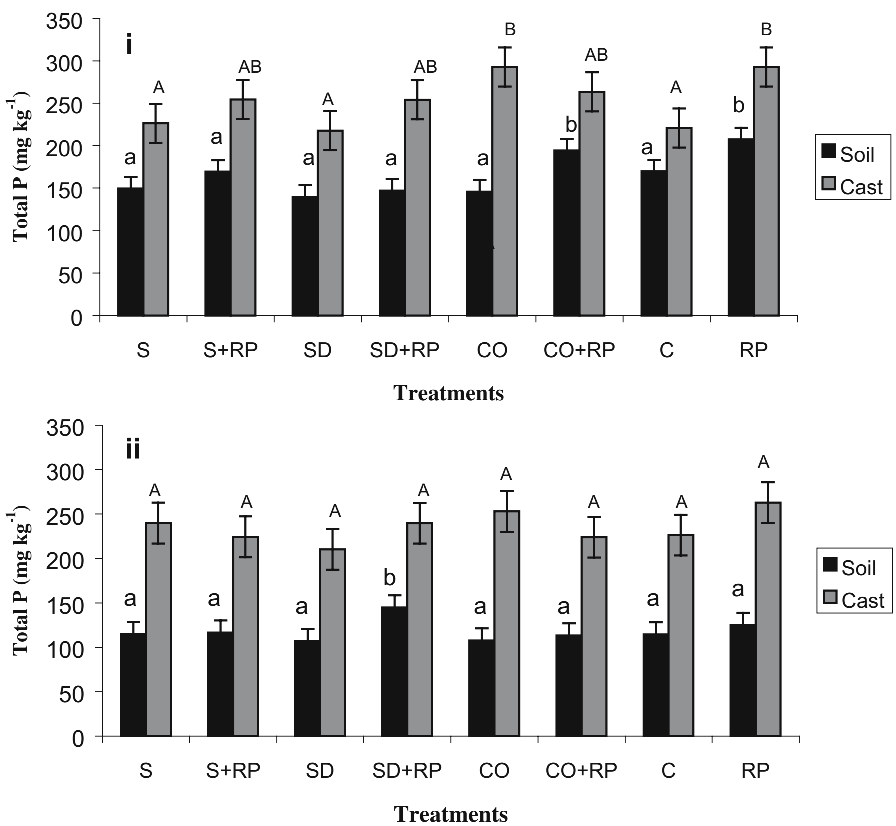

Fig. 2 Total P content of earthworm casts and the surrounding soil for combinations of organic resources and phosphate rock 2 months after sowing (flowering) (**a**) and at harvest (**b**) in 2000 at Kaibo, Burkina Faso. *Bars* represent ±SEM. Treatments with the *same letter* are not significantly different at the 5% level. *Lower case letters* compare soil P content, *upper case letters* compare cast P content. For abbreviations, see Fig. 1

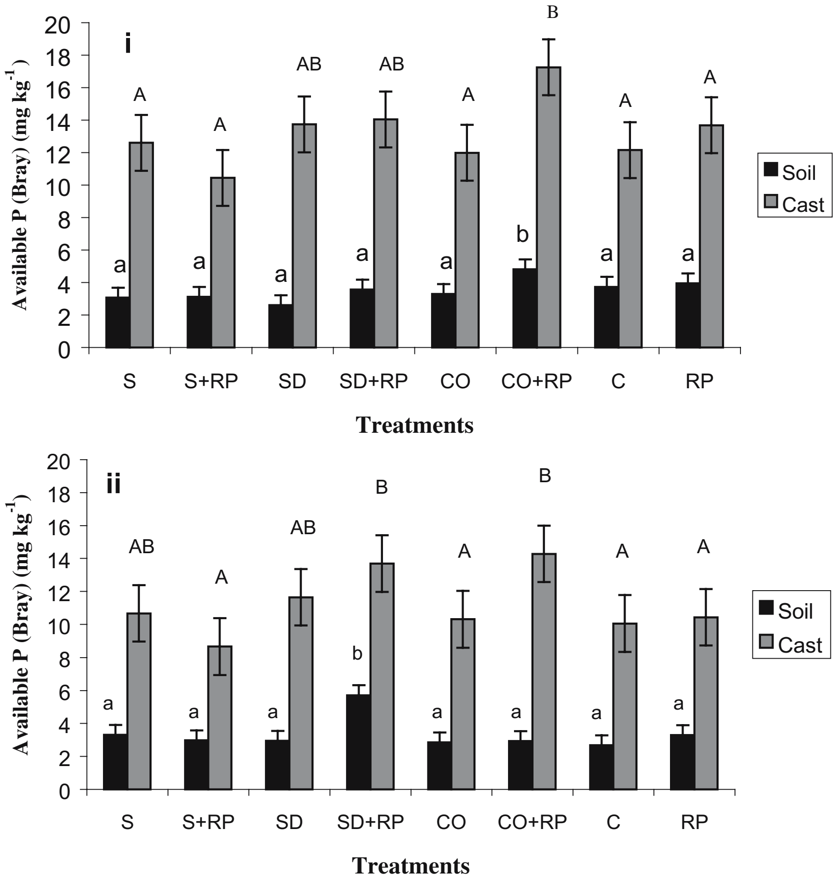

Fig. 3 Available P (Bray) in earthworm casts and in the surrounding soil for combinations of organic resources and phosphate rock 2 months after sowing (**a**) and at harvest (**b**) in 2000 at Kaibo, Burkina Faso. *Bars* represent ±SEM. Treatments with the *same letter* are not significantly different at the 5% level. *Lower case letters* compare soil P content, *upper case letters* compare cast P content. For abbreviations, see Fig. 1

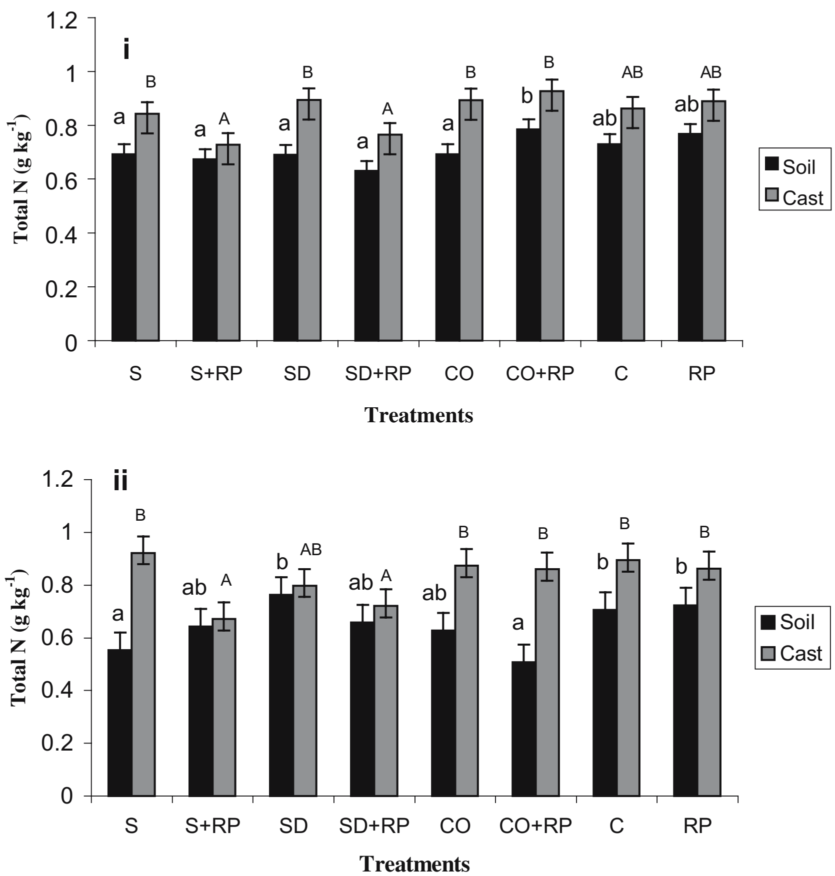

Fig. 4 N content in earthworm casts and in the surrounding soil for combinations of organic resources and phosphate rock 2 months after sowing (flowering) (**a**) and at harvest (**b**) in 2000 at Kaibo, Burkina Faso. *Bars* represent ±SEM. Treatments with the *same letter* are not significantly different at the 5% level. *Lower case letters* compare soil P content, *upper case letters* compare cast P content. For abbreviations, see Fig. 1

Table 4 Sorghum performance in 2000 at Kaibo, Burkina Faso. Data followed by the *same letter* within a column are not significantly different at $P<0.05$. For abbreviations, see Table 2

Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index
S	770 a	3,108 a	0.25 b
S+RP	966 b	3,141 a	0.31 c
SD	910 ab	3,782 a	0.24 b
SD+RP	793 a	3,900 ab	0.20 a
CO	864 ab	3,640 a	0.24 b
CO+RP	770 a	4,097 b	0.19 a
C	902 ab	3,702 a	0.24 b
RP	810 a	3,081 a	0.26 b

Organic resource and phosphate rock interacted significantly in their effects on sorghum grain yield whereas sorghum straw yield was significantly influenced by organic resource quality (Table 3).

Discussion

After the application of organic materials earthworm casting intensity was highest initially and declined over time, probably because earthworm activity was positively affected by degradable organic materials which decompose first followed by the recalcitrant components. The early high peak of cast production in the control reflects the period of trial establishment effects (beginning of the rainy season). Tian et al. (1997) showed that easily decomposable organic material attracts more earthworms at an early stage of decomposition.

The highest earthworm casting intensity in the presence of sheep dung may be due to a greater availability of nutrients. In the compost treatment, comminution by earthworms was probably less needed than for other organic resources as the material was previously broken down during the composting process. Moreover, with regard to the quantity applied, compost had no mulching impact, so it did not create a microclimate that would enhance earthworm activities. These factors may explain why there was no additional earthworm casting intensity in the compost treatments compared with the control. However, no difference in cast weight was observed compared to the other treatments indicating that earthworm nutrition was the same as in the other treatments.

Surface-applied maize straw improves soil water content and has a positive impact on the activity of soil fauna (Mando et al. 1996; Mando 1997). Tian et al. (1997) also demonstrated that the intensity of earthworm activity depends on temperature and soil moisture. Therefore, in the maize straw plots, microclimate and enhanced moisture may be responsible for the enhanced earthworm casting intensity compared with the control.

The low amount of P in earthworm casts reflects the P deficiency in most West African soils. There is a tendency for total cast number, total cast weight and P amount in casts to be lower in the +RP vs. −RP treatments. This may be due to less soil ingestion by earthworms caused by the possibly higher quality of food for earthworms in the +RP treatments. The difference is, however, significant in only one case (SD+RP vs. SD for total cast number and weight; S+RP vs. S for cast P; Table 2) and there is no main effect of RP according to the ANOVA in Table 3. Interestingly, however, there is an interaction effect of organic resource×RP on cast P content and cast Bray P (Table 3). This is reflected in Fig. 3, where Bray P in casts in SD+ RP and CO+RP is significantly higher than in S+RP and RP. This suggests that with high-quality organic resource addition, the plant may benefit more from RP than with low-quality organic resource addition, as a result of earthworm activity.

We hypothesise that less soil was ingested by earthworms in S+RP because the addition of phosphate rock to slowly decomposable organic material (C:N=58) enhanced microbial N immobilisation, thereby limiting earthworm nutrition. This may also explain the lowest N content in earthworm casts in S+RP. Further investigations are needed to verify this hypothesis.

A single application of organic material did not significantly change the content of the soil available P at the two sampling dates. This is due to the low P content of the applied organic materials which contributed to only 9 kg ha^{-1} of total P in the P-deficient poor soil. Addition of phosphate rock to organic materials, however, significantly increased soil P availability and the timing of P availability depended on the quality of the applied organic material. Compost and sheep dung showed positive effects on soil P availability after phosphate rock addition. Probably the low C:N ratio of organic material (compost, C:N=10) favoured microbial activity resulting in a higher release of available P from the phosphate rock (Mackay et al. 1983). It may be concluded that phosphate rock combined with slowly decomposable organic material is not a suitable means of increasing P availability within 1 year of cropping.

The highest available P levels in the earthworm casts reflect the key role of soil fauna in nutrient dynamics and availability (Mackay et al. 1982, Henrot and Brussaard 1997). Mulongoy and Bedoret (1989) reported that earthworm casts have higher enzyme (such as urease and phosphatase) and microbial activities than those of the surrounding soil. Probably these differences were responsible for the higher content of available P in earthworm casts than in surrounding soil, and especially after phosphate rock addition. This also indicates that the contribution of earthworms to the available-P pool mainly occurred through their casts. Total P content of earthworm casts did not vary between the treatments. This confirms the above hypothesis that low soil ingestion by earthworms did not reduced P ingestion after phosphate rock addition as a consequence of high food quality (more P). This indicates that the lower available P of earthworm casts in the S+RP treatment was not due to less P ingestion but to P immobilisation as a consequence of the ingestion of slowly decomposable organic material.

The low sorghum grain yields may be attributed to insufficient rainfall in 2000. The highest grain yield in the S+RP treatment can be attributed to the highest nutrient utilisation efficiency as shown by a high harvest index (Janssen and Wienk 1990). Water stress at the maturing period may limit nutrient transfer from straw and leaves to grains and this can reduce the nutrient utilisation efficiency. Under semi-arid conditions, in a year of insufficient rainfall during the last stage of crop growth, lower biomass crops may produce more grain yield than higher biomass crops because water shortage cannot sustain the high biomass (Pieri 1989; Lawson and Sivakumar 1991). This may also explain the lowest harvest index in CO+RP and SD+RP. We suggest that in a year with a well-distributed rainfall, combining phosphate rock with easily decomposable organic material will have a more beneficial impact on crop performance than combining it with a slowly decomposable organic material.

Despite the constraint of soil pH, which was not optimal for phosphate rock dissolution, our results show that cast-available P may increase by up to fourfold the available P in surrounding soil. This shows the key role of earthworm casts in releasing P from phosphate rock in low-chemical-input agricultural systems.

Integrating earthworms and phosphate rock with decomposing organic material (e.g. composting) may contribute to improved P availability for crop production and help solve the problem of phosphate rock blowing away when directly applied in the field.

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