



Maize growth and production as influenced by earthworm-based integrated soil fertility management in tropical agro-ecosystems

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ABSTRACT

Objectives: To investigate (i) the role of earthworm communities in the integrated soil fertility management (ISFM) theory, and (ii) the mechanisms underlying the positive impact of earthworms on maize production.

Methodology and results: A field mesocosm experiment was set up in a degraded agro-ecosystem in semi-deciduous forest areas in Central-West Côte d'Ivoire. Earthworm communities were composed of the association of decompacting (*Hyperiodrilus africanus*) and compacting (*Millsonia omodeoi*) native species known to be main species in natural populations and regulating soil structure in the area. In the presence of earthworms, there were significant increases in (i) maize growth 30 days after planting, and (ii) maize production (aboveground biomass, grains and root biomass). This significant impact was enhanced with inorganic fertilizers and/or earthworm inoculations. The increase in maize production in earthworm-based treatments is likely to be explained by increasing root biomass production, phosphorus and water use efficiency associated with earthworm engineering activities.

Conclusions and potential application of findings: These findings highlight the crucial role played by earthworms in the ISFM theory through their engineering activities by enhancing the use of water and mineral fertilizers by maize roots. Farmers should encourage proliferation of earthworm populations in their fields as these fauna are important for sustainable agriculture production in agricultural systems.

Keywords: Earthworms, ISFM, nutrient use efficiency, water use efficiency, mesocosms

INTRODUCTION

Integrated soil fertility management (ISFM) is advocated to be one of the best options for sustainable agricultural production in traditional farming systems in Sub Saharan Africa (Vanlauwe *et al.*, 2010) as it promotes farming systems adapted to local conditions and based mainly on the use of organic inputs, mineral fertilizers and improved germplasm. In this technology, the role of soil macroinvertebrates such as earthworms and termites, referred to as soil engineers, in nutrient

cycling, water flow regulation, fertilizer and water use efficiency enhancement may be crucial (Scheu 2003; Lavelle *et al.*, 2006; Ouédraogo *et al.*, 2006). Apart from a recent study showing the enhancement of water and nutrient use efficiency of sorghum in the presence of termites in semi-arid West Africa (Ouédraogo *et al.*, 2006), very few investigations have been focused on this subject. It is therefore important to assess the beneficial impact of ISFM on soil health properties as stated

by Vanlauwe *et al.* (2010). For example, Gilot-Villenave *et al.* (2010) argued that the long-term addition of chemical fertilizers alone to the soil would favour build up of phytophagous nematode communities that represent a threat to cropping without allowing soil C content maintenance.

There is a large body of literature documenting the positive impacts of tropical earthworms on food crop production in field mesocosms (Spain *et al.*, 1992; Pashanasi *et al.*, 1996; Derouard *et al.*, 1997) and enclosures (Gilot-Villenave *et al.*, 1996). Among these observations, only Derouard *et al.* (1996) have attributed yield increase to the interaction between two contrasting functional earthworms (compacting versus decompacting species) resulting in positive impact on water infiltration rate and aggregate size distribution (Blanchart *et al.*, 1997). This preliminary observation needs to be confirmed by other studies in the light of new theories in soil fertility management highlighting the positive impact of the combined effect of earthworms and fertilizers on plant productivity (Laossi *et al.*, 2009).

A field mesocosm experiment was set up in a degraded agro-ecosystem in semi-deciduous forest areas in Center-West Ivory Coast to determine how associations between earthworms and mineral fertilisers influence maize productivity. Earthworm communities were composed of the association of decompacting and compacting native species known to be the main feature in natural populations (Rossi, 2003) and regulating soil structure (Blanchart *et al.*, 1997). The objectives of this study were: (i) to investigate the role of earthworm communities in the ISFM theory, and (ii) to find out mechanisms underlying their positive impact on maize production. We hypothesized that maize growth and production enhancement is due to a combined effect of earthworms and inorganic fertilizers which (i) increases earthworm engineering activities with the consequence of improving ecosystems services; and (ii) enhances fertilizer and water use efficiency by the crop.

MATERIALS AND METHODS

Study site description: The study was carried out from September to November 2009 at Goulrikao (5°28'59"N, 6°31'13"W, elevation 177 m), a village located in semi-deciduous forest areas in the Centre-West of Côte d'Ivoire, precisely in a 2 year-old fallow which is the most common transitional agro-ecosystem in the area. The climate is sub-equatorial with 1354.6 mm rainfall during the study year and an average monthly temperature of 26°C. The long dry season takes place from November to February; the long rainy

season from March to June; the short dry season from July to August and the short rainy season from September to October. Total rainfall during the study period was about 162.6 mm. Soils are Ferralsols (World Soil Reference, 2006) with differences due to topography (Assié *et al.* 2008). According to the chemical properties (Table 1) the soil is slightly acidic and characterized by low fertility. They are similar to values obtained in a secondary forest in Central Ivory Coast (Gilot-Villenave *et al.* 1996).

Table 1: Chemical characteristics (Mean \pm SE) of the topsoil (0-10 cm) of the experimental site. CEC: Cation exchange capacity.

Parameter	Value
pH (Water)	6.8 \pm 0.1
Organic C (g kg ⁻¹)	14.8 \pm 1.8
Total N (g kg ⁻¹)	1.1 \pm 0.1
C/N	13.46 \pm 2.44
Total P (mg kg ⁻¹)	149.58 \pm 17.3
Available P (mg kg ⁻¹)	23.52 \pm 2.36
CEC (cmol _c kg ⁻¹)	6.19 \pm 1.24
Ca (cmol _c kg ⁻¹)	3.43 \pm 0.64
Mg (cmol _c kg ⁻¹)	1.70 \pm 0.35
K (cmol _c kg ⁻¹)	0.22 \pm 0.02

Earthworms: Two native earthworm species common in degraded agro-ecosystems of the study area (Tondoh *et al.*, 2007) were selected: (i) *Millsonia omodeoi* (Acanthodrilidae) a large mesohumic compacting species (Fig. 1a) which may be 15-20 cm long and weigh 5-6 g fresh weight at the adult stage (Blanchart *et al.*, 1999), and (ii) *Hyperiodrilus africanus* (Eudrilidae) a slightly pigmented polyhumic

decompacting species (Fig. 1b) which may be 8-15 cm long, weighing up to 1 g fresh weight at the adult stage (Tondoh & Lavelle, 2005). *H. africanus* is considered as decompacting species because of the loose cast produced, while *M. omodeoi* is called compacting species due to the production of massive and globular casts.



Figure 1: Different earthworm species inoculated: (a) *Millsonia omodeoi* and (b) *Hyperiodrilus africanus*

Both earthworm species were chosen because they were already used in similar experiments (Spain *et al.*, 1992; Gilot-Villenave *et al.*, 1996; Derouard *et al.*, 1997). Moreover, data on their biology and demography (Lavelle, 1981; Tondoh & Lavelle, 1997; Tondoh, 1998; Tondoh & Lavelle, 2005) and their impact on soil structure (Blanchart *et al.*, 1997) have been well documented in the past fifteen years. Only adults or subadults species were used in the experiment in order to increase the survival rate of populations.

Test crop: The test crop selected is yellow maize (PIONEER variety) produced from the cross between “Bouaké yellow variety” and “IRAT 8 white variety”. This variety was chosen because of its short growth cycle (3 months) and its growing interest in local farming systems as a food crop. The value of maize is obvious as prices of cocoa are still low and more people are now using maize as food and short-term cash crop.

Fertilizers: Urea (46% N) and superphosphate (45% P) were used as fertilizers and applied at the soil surface at the rate of 0.9 and 0.55 g per plant, respectively. This corresponds to 161 kg of N and 67 kg of P per hectare. The levels of these chemical inputs approximately correspond to the recommended

amounts in tropical soils (Vanlauwe & Giller, 2006). Superphosphate was applied once during maize sowing, while 1/3 of urea was applied during sowing and the last 2/3 was applied 40 days after planting (DAP) as recommended for Ferralsols (Kang, 1997).

Experimental design: The experimental unit was a mesocosm made of a plastic bucket (inner diameter 24 cm, height 50 cm) buried 45 cm deep and extending 5 cm above the soil surface. The bottom of the container was scattered with holes and laid on a bed of stones to allow water to flow out.

Containers were filled up with 10 kg of soil taken from the upper 10 cm in the 2 year-old-fallow around the study plot, sieved at 2 mm to remove earthworms and other macrofauna, thoroughly homogenized and moistened to field capacity (16 % dry weight).

The experimental design consisted of a set of 40 mesocosms representing 8 treatments with 5 replicates set-up in the 2 year-old fallow. The eight treatments were arranged in randomized block design made of 5 blocks, each corresponding to a replicate. Within the experimental design, the blocks were separated by 2 m while an interval of 1 m was observed between mesocosms.

The following treatments were included in the experimental design:

- Maize (control), Mz;
- Maize + urea, Mz+U;
- : Maize + superphosphate, Mz+S;
- Maize + urea + superphosphate, Mz+U+S;
- Maize + earthworms, Mz+Ew;
- Maize + earthworms + urea, Mz+Ew+U;
- Maize + earthworms + superphosphate, Mz+Ew+S;
- Maize + earthworms + urea + superphosphate, Mz+Ew+U+S.

Maize was sown at a density of 1 plant per bucket. In all earthworms-based treatments, the two earthworm species namely *M. omodeoi* and *H. africanus* were always simultaneously inoculated in order to benefit from their positive impact on soil structure regulation (Blanchart *et al.*, 1997; Derouard *et al.*, 1997). The first inoculation of earthworms was done 5 days before sowing maize at the rate of 3 adults of each species (or biomass of 16.5 and 3 g for *M. omodeoi* and *H. africanus*, respectively); the second inoculation happened 15 DAP at a rate of 2 adults per species (biomass of 11 and 2 g for *M. omodeoi* and *H. africanus*, respectively). The third inoculation happened 30 DAP at the same rate while the last one took place 45 DAP at a rate of 4 adults per species. In total, 22 individuals corresponding to a total biomass of 71.5 g (60.5 and 11 g for *M. omodeoi* and *H. africanus*, respectively) were inoculated in each earthworm-based treatment (Mz+Ew, Mz+Ew+U, Mz+Ew+S and Mz+Ew+U+S).

The buckets were buried in the 2 year-old *C. odorata*-based fallow, fenced with palm-oil tree leaves and were left in the open air where watering was ensured by natural rainfall during the three months. The experimental cells were kept clean by manual weeding every 15 days.

Soil physical properties: At the end of the experiment (3 months), soil penetration resistance coupled with bulk density were measured as physical variables in 1/4 bucket at 2 different depths i.e. 0-10 cm and 10-20 cm.

The penetration resistance was measured using a cone pocket penetrometer type Yamanaka (Assié *et al.*, 2008). The cone is gently pressed horizontally against the wall of each soil layer and the measured value was expressed as pressure (kPa) required for the penetration of the cone into the soil.

Bulk density of 0-10 cm and 10-20 cm layers was estimated using the cylinder method. Soil was sampled with a 6 cm diameter and 10 cm height metal cylinder.

The sample was then oven-dried at 105°C for 48 hours and weighed to get the dry weight (DW). Bulk density (BD) was calculated as following: $BD = DW/V$, where BD (g/cm³), DW (g) and V is the cylinder volume (cm³).

Earthworm survival: Remaining *M. omodeoi* and *H. africanus* were collected, counted and weighed alive to assess their survival rate and fresh biomass.

Maize growth and production: During the experiment, maize height was determined 30, 50 and 75 DAP. After measuring the physical parameters and collecting soil samples for chemical analyses, maize plants were harvested, oven-dried for 2 days at 75°C and weighed. Then roots, aboveground biomass and grains were weighed separately.

Nutrients and water use efficiencies: The impact of earthworm communities on maize nutrient (nitrogen and phosphorus) and water use efficiencies in the different earthworm-based treatments were calculated as per a recent study (Ouédraogo *et al.*, 2006). In the present work, only 5 treatments were considered for calculation of these agronomic parameters, i.e. Control, Maize + urea, Maize + superphosphate, Maize + earthworms + urea and Maize + earthworms + superphosphate. Calculations were done as follows:

Maize water use efficiency (WUE) = (Aboveground biomass in the treatment – aboveground biomass in the control without earthworms) (kg.ha⁻¹) / Total rainfall during the study period (mm).

Nitrogen use efficiency (NUE) = (Maize grain yield in the treatment – maize grain yield in the control without earthworms) (kg ha⁻¹) / Equivalent total nitrogen applied (kg ha⁻¹).

Phosphorus use efficiency (PUE) = (Maize grain yield in the treatment – maize grain yield in the control without earthworms) (kg ha⁻¹) / Equivalent total phosphorus applied (kg ha⁻¹).

Statistical analysis: We checked the homogeneity of variance (Levene's test) and normality of the distribution (Shapiro-Wilk's test) for soil physical parameters, maize height and aboveground, grain and root biomasses. When dataset satisfied these conditions, a one-way ANOVA was conducted to test the treatment effect. Otherwise, data were analysed using Kruskal-Wallis test. Spearman's correlation was performed to explore the relationship of the components of each maize plant with earthworm abundance and soil physical parameters. The two earthworm species association effect on nutrients and water use efficiencies by crops was tested by Student t-test. All analyses were performed using STATISTICA 7.0 (Statsoft, Tulsa, USA).

RESULTS

Survival rate of earthworms: Results (table 2) showed the abundance of earthworms inoculated and recovered after the duration of the experiment. After three months, most of *H. africanus* had died, but significant population of *M. omodeoi* were present in all treatments. The survival rate of *H. africanus* populations ranged between 0 - 4.6% with an average value of 1.2%. *M. omodeoi* populations had high

survival rates between 54.6 and 72.2% which averaged 65.9%.

An increase in earthworms global biomass was recorded in the Mz+Ew+U (88.34±11.1 g) and Mz+Ew+S (90.54±11.3 g) treatments, compared to the total initial biomass of about 71.5 g. The biomass of *M. omodeoi* species had increased in all the treatments.

Table 2: Abundance of inoculated and recovered earthworm species per treatment and the associated survival rates.

	Inoculated individuals per treatment				
	Mz+Ew	Mz+Ew+U	Mz+Ew+S	Mz+Ew+U+S	
<i>M. omodeoi</i>	11	11	11	11	
<i>H. africanus</i>	11	11	11	11	
Total	22	22	22	22	
	Recovered individuals per treatment				
	Mz+Ew	Mz+Ew+U	Mz+Ew+S	Mz+Ew+U+S	
<i>M. omodeoi</i>	6.6 ± 1.4	8.4 ± 1.1	8.4 ± 1	5.8 ± 1.3	
<i>H. africanus</i>	0	0	0.6±0.4	0	
Total	6.6 ± 1.4	8.4 ± 1.1	9 ± 1.2	5.8 ± 1.3	
	Recovered biomass (g) per treatment				
	Mz+Ew	Mz+Ew+U	Mz+Ew+S	Mz+Ew+U+S	
<i>M. omodeoi</i>	66 ± 13.6	84.2 ± 11.2	89.34 ± 11	62.14 ± 12.4	
<i>H. africanus</i>	0	0	1.2 ± 0.8	0	
Total	70.14 ± 11.6	88.34 ± 11.1	90.54 ± 11.3	62.14 ± 12.4	
	Survival rates (%)				
	Mz+Ew	Mz+Ew+U	Mz+Ew+S	Mz+Ew+U+S	
<i>M. omodeoi</i>	63.6	72.7	72.7	54.6	
<i>H. africanus</i>	0	0	4.6	0	

Mz+Ew = Maize+earthworms; Mz+Ew+U = Maize+earthworms+urea; Mz+Ew+S = Maize+earthworms+superphosphate; Mz+Ew+U+S = Maize+earthworms+urea+superphosphate.

Impact of earthworms on soil physical properties:

Trends observed in both strata were similar as soil penetration resistance significantly increased in treatments inoculated with earthworms. However, the rise was significantly marked in the 10-20 cm layer only (Table 3) with highest values ranging between 1943.9 kPa in the treatment Mz+Ew+U and 2361.57 kPa in Mz+Ew, relative to the control "Mz" (538.51±99.14

kPa). Furthermore, the general tendency was of much higher average values in the 10-20 cm layer.

The variation in bulk density values between all treatments was not significant (Table 3) in both depths, though the lowest values were obtained in the Mz+Ew+U+S treatment (0-10 cm: 0.67±0.01 g cm⁻³, 10-20 cm: 0.72±0.01 g cm⁻³) characterized by biological and mineral fertilizer inputs.

Table 3: Soil physical properties (Mean ± SE) in two strata of soil with varying treatments.

Treatments	Resistance to penetration (kPa)		Bulk density (g.cm ⁻³)	
	0 – 10 cm	10 – 20 cm	0 – 10 cm	10 – 20 cm
Mz	201.32±4.05 a	538.51±99.14 a	0.73±0.01 a	0.76±0.01 a
Mz+U	203.19±27.93 a	858.34±150.09 a	0.72±0.01 a	0.75±0.02 a
Mz+S	239.82±68.75 a	980.31±201.14 a	0.69±0.02 a	0.75±0.03 a
Mz+U+S	230.62±24.09 a	819.25±166.86 a	0.72±0.01 a	0.79±0.01 a

Mz+Ew	324.12±23.50 a	2361.57±250.08 b	0.7±0.03 a	0.75±0.01 a
Mz+Ew+U	283.38±65.15 a	1943.9±485.82 b	0.69±0.02 a	0.75±0.03 a
Mz+Ew+S	218.5±30.61 a	1985.63±354.28 b	0.71±0.02 a	0.75±0.02 a
Mz+Ew+U+S	269.29±30.86 a	2268.91±349.12 b	0.67±0.01 a	0.72±0.01 a

Mz: Maize (control), Mz+U: Maize + urea, Mz+S: Maize + superphosphate, Mz+U+S: Maize + urea + superphosphate, Mz+Ew: Maize + earthworms, Mz+Ew+U: Maize + earthworms + urea, Mz+Ew+S: Maize + earthworms + superphosphate, Mz+Ew+U+S: Maize + earthworms + urea + superphosphate.

Standard errors in parentheses. Values followed by different letters along the columns are significantly different at $P=0.05$ one-way ANOVA.

Impact of earthworms on maize growth: In general maize heights increased from 30 to 75 DAP for each treatment. However, the variation of the mean values of height between the eight treatments was only significant at 30 DAP (Fig. 2). Mesocosms inoculated with earthworms and/or fertilized showed higher plant height than the control (35.3±4.9 cm). The highest plant height was in Mz+Ew+U treatment (59.8±4.40 cm), showing the beneficial effect of integrated inputs. It was followed by maize amended with inorganic fertilizer only (Mz+U+S: 56.26±1.76 cm), the mixture of biological and inorganic fertilizer inputs (Mz+Ew+U+S: 55.98±2.15 cm) and maize only inoculated by earthworms (53.48±2.45 cm). Earthworms increased maize height but their impact was amplified by the addition of chemical fertilizers.

No significant differences were observed between the treatments over 50 days. However, the highest value of height was found in "Mz+U+S" (107.7±13.07 cm) compared to the control "Mz" (89.6±3.58 cm). Similarly, no significant differences were observed between the various treatments at 75 DAP (Fig. 2), though the highest value (199±6.75 cm) was obtained in mesocosms characterized by earthworms presence and mineral fertilizer inputs.

Impact of earthworms on maize production: Maize aboveground biomass was likewise significantly (Kruskal-Wallis test, $P = 0.048$) higher in buckets inoculated with earthworms and/or associated with inorganic fertilizers (Fig. 3a). The increase rates, compared to the control, were 171.2, 62.2, 59.9, 53.3 and 35.5% in treatments Mz+Ew, Mz+Ew+U+S,

Mz+U+S, Mz+Ew+U and Mz+Ew+S, respectively. The highest values 10.63±4.41 t ha⁻¹, 6.36±1.94 t ha⁻¹ and 6.24±1.86 t ha⁻¹ were obtained in the Mz+Ew, Mz+Ew+U+S and Mz+U+S treatments, respectively.

The presence of earthworms alone or combined with fertilizers significantly increased maize grain production (Kruskal-Wallis test, $P = 0.0183$) relative to the control. Rates of increase ranged from 58.8 (Mz+S) to 111.04% (Mz+U+S) in fertilizer-based treatments, from 92.64 (Mz+Ew+S) to 122.09% (Mz+Ew+U) in the combined earthworms and chemical fertilizers input, and about 266.9% (Mz+Ew) in earthworm-based treatment (Fig. 3b). Values of maize yield were as ranked in the following decreasing order: Mz+Ew: 5.98±3.84 t ha⁻¹ > Mz+Ew+U: 3.62±3.4 t ha⁻¹ > Mz+U+S: 3.44±1.4 t ha⁻¹ > Mz+Ew+U+S: 3.2±1.77 t ha⁻¹ > Mz+Ew+S: 3.14±2.18 t ha⁻¹ > Mz+S: 2.59±1.08 t ha⁻¹ > Mz: 1.63±1.06 t ha⁻¹ > Mz+U: 1.41±0.52 t ha⁻¹.

Earthworms (Mz+Ew) and their association with fertilizers (Mz+Ew+U+S) significantly improved root biomass production (Kruskal-Wallis test, $P < 0.0028$) by 1.9-fold and 1.2-fold, respectively. Root biomass was lower in Mz+Ew+S (0.9±0.13 t ha⁻¹), Mz+Ew+U (1.34±0.17 t ha⁻¹), Mz+U (1.47±0.13 t ha⁻¹) and Mz+U+S (1.60±0.32 t ha⁻¹) than in treatments with earthworms (3.38±0.36 t ha⁻¹) and earthworms + fertilizers-based treatments (2.21±0.19 t ha⁻¹) (Fig. 3c). Furthermore, a significant relationship ($R^2 = 0.1402$, $N = 40$, $P = 0.0173$) was found between root biomass and the resistance to penetration in the topsoil layer (Fig. 4) showing the development of roots in the soil layer characterized by lower soil compaction.

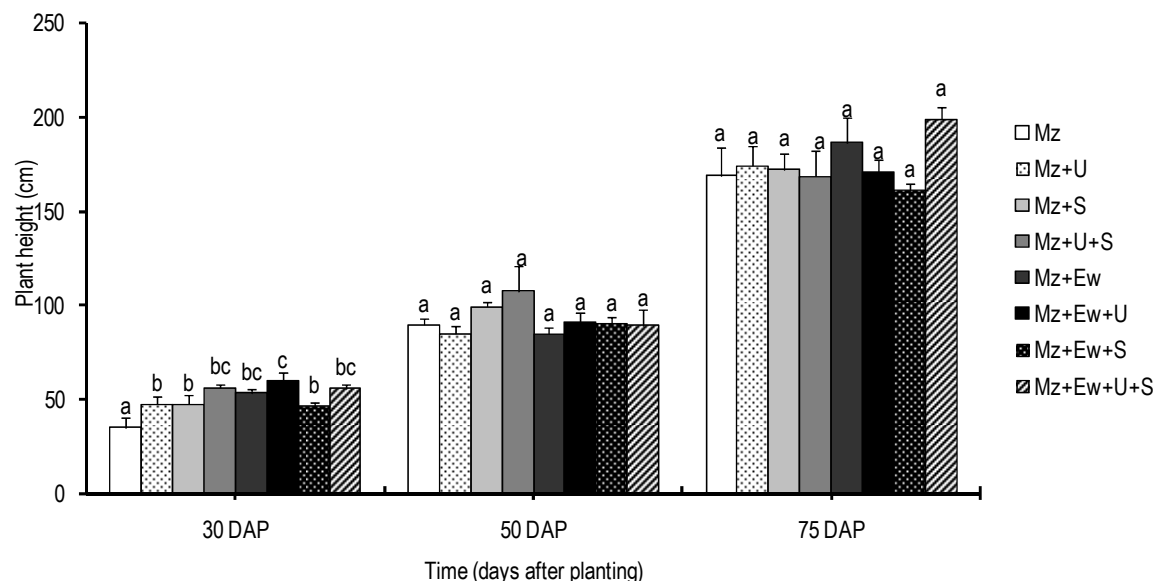
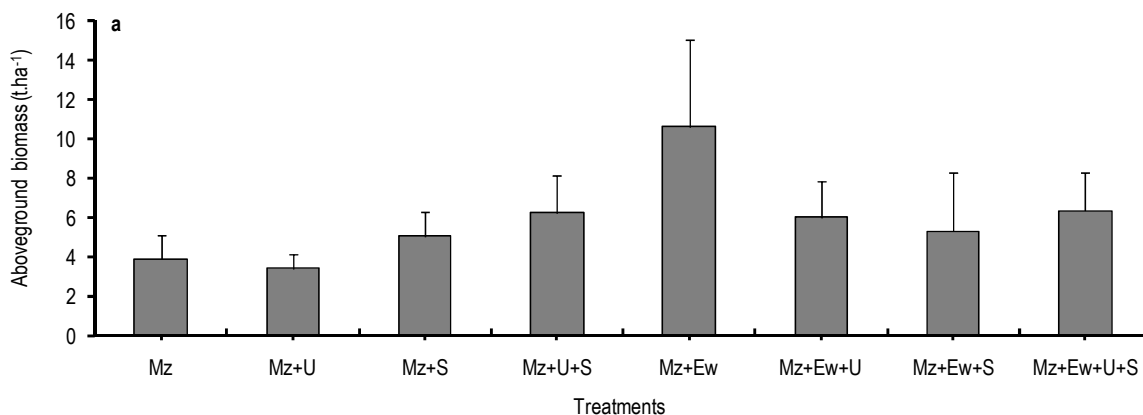


Figure 2: Height of maize plants at 30 – 75 days after planting (DAP). Means with different letters indicate a significant difference at $P=0.05$ level (One-way ANOVA).

Mz: Maize (control), Mz+U: Maize + urea, Mz+S: Maize + superphosphate, Mz+U+S: Maize + urea + superphosphate, Mz+Ew: Maize + earthworms, Mz+Ew+U: Maize + earthworms + urea, Mz+Ew+S: Maize + earthworms + superphosphate, Mz+Ew+U+S: Maize + earthworms + urea + superphosphate.

Impact of earthworms on nitrogen, phosphorus and water use efficiencies: Earthworms inoculation induced a slight reduction in maize NUE as the value in the control treatment without earthworms was about $55.92 \pm 12.8 \text{ kg kg}^{-1}$ against $53.6 \pm 14.4 \text{ kg kg}^{-1}$ (Fig. 5a) in treatments with earthworms. Contrary to NUE, earthworms significantly (Student's test; $P = 0.0095$) enhanced maize PUE by 275.4% (Fig. 5a). Value obtained in treatment with earthworms ($118.9 \pm 50.5 \text{ kg.kg}^{-1}$) was 4-fold higher than that without earthworms ($31.7 \pm 12.8 \text{ kg kg}^{-1}$).

Moreover, the presence of earthworms had no significant impact on maize WUE in nitrogen-based treatments regardless of the presence of earthworms as the values were 0.0185 ± 0.007 and $0.0193 \pm 0.007 \text{ kg mm}^{-1}$ (Fig. 5b). On the contrary, maize WUE was improved by earthworms in phosphorus-enriched treatment (Student's test; $P = 0.0058$) such that the values increased significantly from $0.0101 \pm 0.005 \text{ kg mm}^{-1}$ to $0.0257 \pm 0.015 \text{ kg mm}^{-1}$ with an increase rate estimated at 154.46%.



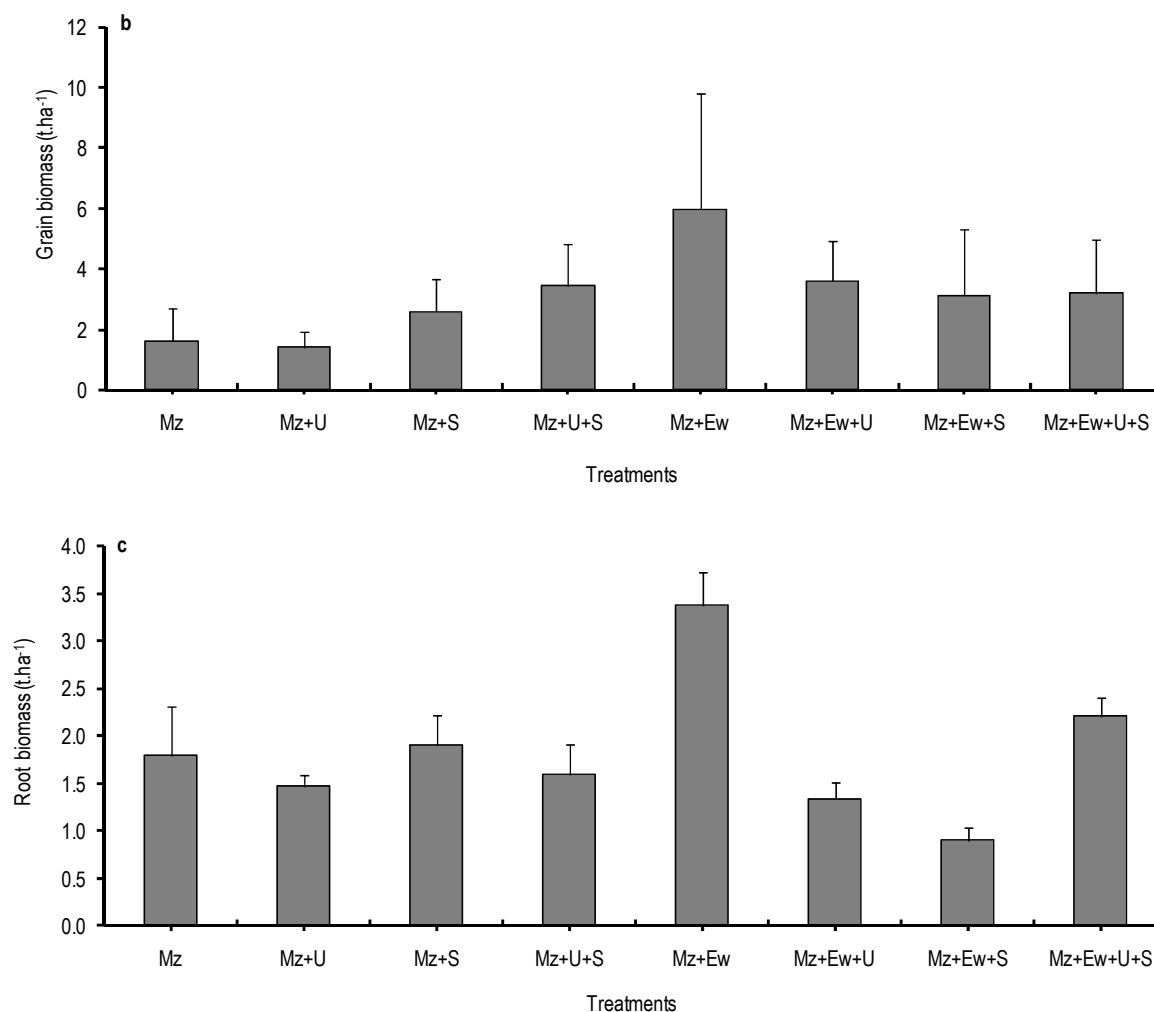


Figure 3: Maize production in different treatments: (a) aboveground biomass, (b) grain biomass, and (c) root biomass. Refer to Figure 1 for legend.

DISCUSSION

The co-inoculation of both earthworm functional groups was detrimental to *H. africanus* populations as their survival rate was extremely low at the end of the experiment (1.4%) compared with *M. omodeoi* (66.4%). Moreover, the development of the body mass of *M. omodeoi* individuals in all earthworms-based treatments suggests that this species is the main contributor to soil process. Two reasons are likely to explain *H. africanus* low survival rates: (i) demographic strategies by which *H. africanus* individuals exhibits r-strategy with low survival rate (Tondoh & Lavelle, 2005), on the contrary of the k-strategy displayed by *M. omodeoi* and characterized by high survival rate (Lavelle, 1981), and

(ii) interspecific competition between both populations characterized by the reduction of the niche of *H. africanus* that are not able to consume the high rate of macro-aggregates produced by *M. omodeoi*. As a result, the compacting effects of *M. omodeoi* took precedence over the decompacting impact of *H. africanus*. This probably explains the increase in soil compaction in treatments inoculated with earthworms and confirmed the prevalence of negative responses in earthworm interactions suggesting overlap in basic niche requirement and predominance of competition relationships drawn from a meta-analysis by Uvarov (2009).

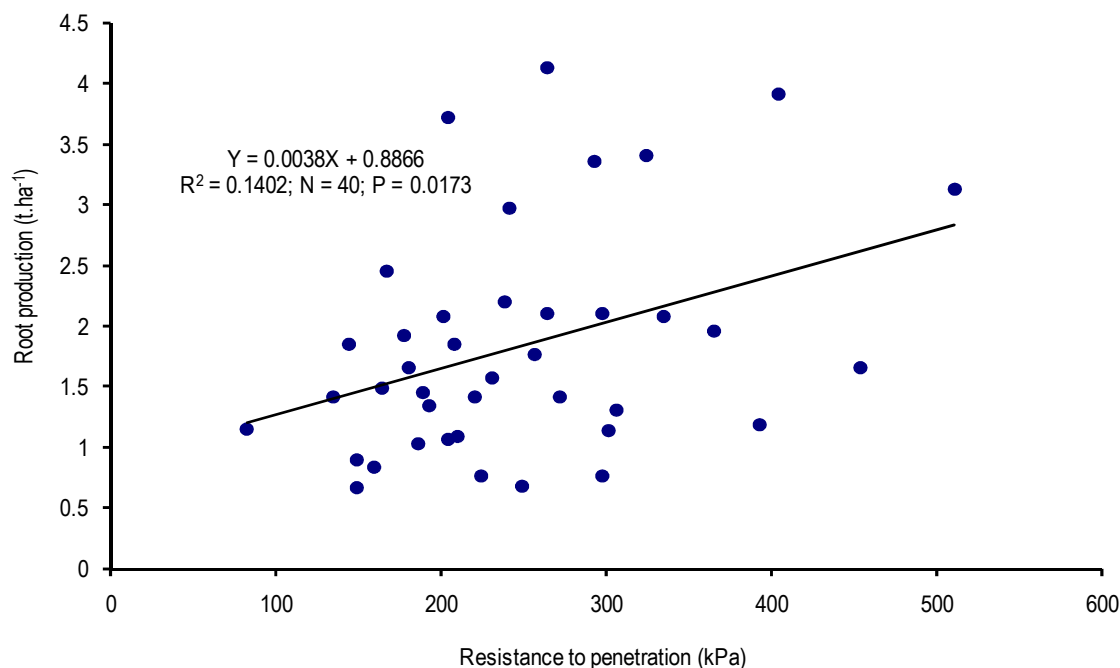
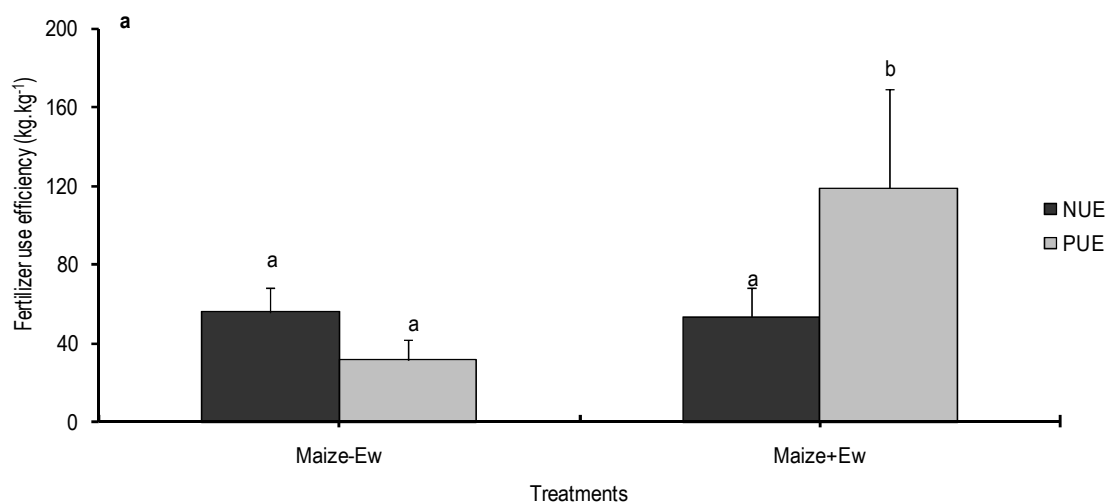


Figure 4: Soil compaction as function of the roots biomass in the top first cm of soil.

In general, the significant impact of earthworms on maize growth 30 DAP, is enhanced by inorganic fertilizer inputs, as the Mz+Ew+U and Mz+Ew+U+S treatments (fertilizer application) showed a slight increase compared to the Mz+Ew treatment (only earthworms). This result may be due to a synergistic effect of the earthworms (*M. omodeoi* + *H. africanus*) and inorganic fertilizers on crop growth. According to Marhan & Scheu (2005) the combination of soil organic matter and mineral fertilizers is a prerequisite to boost

up earthworm activities in temperate ecosystems, as farm yard manure applied in combination with NPK application increase the activity of the endogeic worm *Octolasion tyrtaeum* in Germany by 42.8%. Furthermore, Helling & Larink (1998) observed that N mineralisation in soil was improved by the interaction between earthworms and urea in temperate systems. The positive impact of inorganic fertilizers on maize growth and production was enhanced by the inoculation of earthworms.



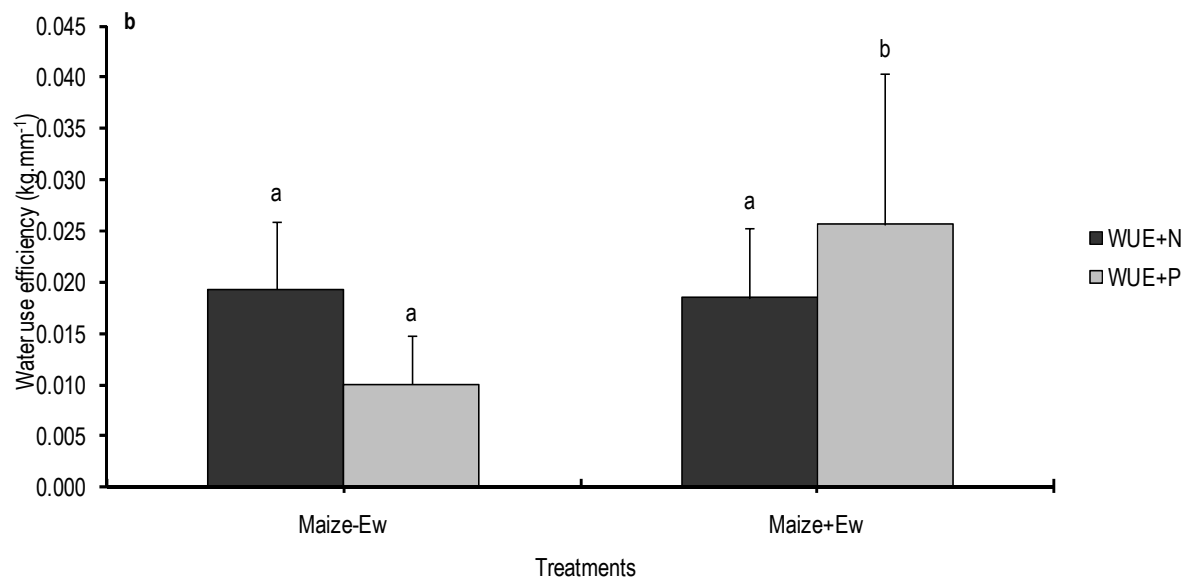


Figure 5: Fertilizers and water use efficiencies of maize in earthworms and no-earthworms treatments. (a) Fertilizers use efficiencies (NUE: nitrogen use efficiency and PUE: phosphorus use efficiency). (b) Water use efficiency (WUE+N: water use efficiency in presence of nitrogen and WUE+P: water use efficiency in presence of phosphorus). Maize-Ew: maize in no-earthworms treatment, Maize+Ew: maize in earthworms treatment. Between the two treatments, values followed by different letters indicate a significant difference at $P=0.05$ level (Student t).

Basically one can argue that earthworms boost soil bioturbation and improve ecosystem services such as water infiltration capacity and root development which in turn enhance phosphorus and water use efficiency. However, the increased maize growth in earthworm-based treatments was restricted within 30 DAP showing there is only a short duration of the beneficial impact of earthworm inoculation. Knowing that 30 days nearly correspond to the 45-days generation time of *H. africanus* (Tondoh, 1998), one can speculate on the active association of this species with *M. omodeoi* that would have positively impacted water infiltration capacity and the reduction of macroaggregates as showed by Derouard *et al.* (1997). In contrast to a general thought that positive effects of earthworm on plant growth are more likely in nutrient poor soils (Brown *et al.*, 2004), our results confirmed recent findings in France on the positive effects of earthworms on soils amended with mineral fertilizers (Laossi *et al.*, 2009).

Maize production, especially aboveground, grain and root biomass were significantly enhanced by earthworms. Previous studies investigating the effect of earthworm addition on crop production drew out similar results (Gilot-Villenave *et al.*, 1996; Derouard *et al.*, 1997; Blouin *et al.*, 2006; Eriksen-Hamel & Whalen,

2007). In a maize-based pot study in Lamto, Derouard *et al.* (1997) found that the addition of earthworms (*M. omodeoi* and *Sthulmannia zielae*) improved leaf production by 23% and increased cob biomass and number by 3-fold and 2.6-fold, respectively.

Among various mechanisms involved in earthworm effects on plants (Scheu, 2003), our study identified increase in root biomass, phosphorus and water use efficiencies to be mostly determinant factors. Earthworm engineering activities in the first 10 cm layer is likely to have created suitable conditions for roots development as shown by the significant relationship between soil compaction and root biomass (Fig. 4). This in turn significantly impacted water and phosphorus uptake. Our results are similar to observations made in Burkina-Faso by Ouédraogo *et al.* (2006) pointing out the positive impact of termites on sorghum PUE and WUE. Indeed, earthworm activities would have improved phosphorus supply in soil by creating easily available organic P pool as demonstrated by Wan & Wong (2004) who noted a quick transformation of organic P into plant-available P forms with exposure to *Pheretima guillelmi* and *Eisenia fetida* activities. The digestive gut of earthworms is able to secrete phosphatase and enhance their activity thus in turn accelerate the available P released in the soil

(Chapius-Lardy *et al.*, 1998; Vinotha *et al.*, 2000; Wan & Wong, 2004; Ernst *et al.*, 2009). In our experiment, the apparent absence of impact of earthworms on NUE

CONCLUSION

This study showed that (i) earthworms play a crucial role in the ISFM theory through their engineering activities by enhancing the use of water and mineral fertilizers by maize roots, and (ii) earthworms can be used as viable biological component in the ISFM framework. These findings highlight the importance of

may be probably due to N immobilization in compact casts produced by *M. omodeoi*.

earthworm management for sustainable agriculture production in agricultural systems. However massive production of earthworms required to implement such cropping systems coupled with farmer participation are the main challenge to address.

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REFERENCES

- Assié KH, Angui KTP, Tamia AJ, 2008. Effet de la mise en culture et des contraintes naturelles sur quelques propriétés physiques ferrallitiques au Centre-Ouest de la Côte d'Ivoire : Conséquences sur la dégradation des sols. *European Journal of Scientific Research* 23 :149-166.
- Blanchart E, Albrecht A, Alegre J, Duboisset A, Gilot C, Pashanasi B, Lavelle P, Brussaard L, 1999. Effects of earthworms on soil structure and physical properties. In: Lavelle, P., Brussaard, L., Hendrix, P. (Eds.), *Earthworm Management in Tropical Agroecosystems*. CAB International, Wallingford, UK, pp 149–172.
- Blanchart E, Lavelle P, Braudeau E, LeBissonnais Y, Valentin C, 1997. Regulation of soil structure by geophagous earthworm activities in humid savannas of Côte d'Ivoire. *Soil Biology & Biochemistry* 29: 431-439.
- Blouin M, Barot S, Lavelle P. 2006. Earthworms (*Millsonia anomala*, Megascolecidae) do not increase rice growth through enhanced nitrogen mineralization. *Soil Biology & Biochemistry* 38: 2063-2068.
- Brown GG, Edwards CA, Brussaard L, 2004. How earthworms affect plant growth: burrowing into the mechanisms. In: Edwards, C.A. (Ed.), *Earthworm Ecology*, pp 13-49.
- Chapius-Lardy L, Brossard M, Lavelle P, Schouller E, 1998. Phosphorus transformations in a ferralsol through ingestion by *Pontoscolex corethrurus*, a geophagous earthworm. *European Journal of Soil Biology* 34: 61-67.
- Derouard L, Tondoh J, Vilcosqui L, Lavelle P, 1997. Effects of earthworm introduction on soil processes and plant growth. *Soil Biology & Biochemistry* 29: 542-545.
- Eriksen-Hamel NS, Whalen, KJ 2007. Impacts of earthworms on soil nutrients and plant growth in soybean and maize agroecosystems. *Agriculture, Ecosystems & environment* 120: 442-448.
- Ernst G, Henseler I, Felten D, Emmerling C, 2009. Decomposition and mineralization of energy crop residues governed by earthworms. *Soil Biology & Biochemistry* 41: 1548–1554.
- Gilot-Villenave C, Lavelle P, Ganry F, 1996. Effects of a tropical geophagous earthworm, *Millsonia anomala*, on some soil characteristics, maize-residue decomposition and on maize production in Ivory Coast. *Applied Soil Ecology* 4: 201-211.
- Gilot-Villenave C, Saj S, Pablo AL, Sall S, Djigal D, Chotte JL, Bonzi M, 2010. Influence of long-term organic and mineral fertilization on soil nematofauna when growing *Sorghum bicolor* in Burkina Faso. *Biology and Fertility of Soils* 46: 659-670.
- Helling B. and Larink O, 1998. Contribution of earthworms to nitrogen turnover in agricultural soil treated with different mineral N-fertilizers. *Applied Soil Ecology* 9: 319-325.
- Kang BT, 1997. Les engrais: Définition et calculs. In: *Guide de phytotechnie de l'IITA*, 28 p

- Laossi K-R, Ginot A, Noguera CD, Blouin M, Barot S, 2009. Earthworm effects on plants growth do not necessarily decrease with soil fertility. *Plant & Soil* 328: 109-118.
- Lavelle P, 1981. Stratégies de reproduction chez les vers de terre. *Acta Oecologica* 2: 117-133.
- Lavelle P, Decaëns T, Barot S, Blouin M, Bureau F, Magerie P, Mora P, Rossi JP, 2006. Soil invertebrates and ecosystem services. *European Journal of Soil Biology* 42: 3-15.
- Marhan S. and Scheu S, 2005. The influence of mineral and organic fertilizers on the growth of the endogeic earthworm *Octolasion tyrtaeum* (Savigny). *Pedobiologia* 49: 239-249.
- Ouédrago E, Mando A, Brussaard L, 2006. Soil macrofauna affect crop nitrogen and water use efficiencies in semi-arid West Africa. *European Journal of Soil Biology* 42: S275-S277.
- Pashanasi B, Lavelle P, Alegre J, Charpentier F, 1996. Effect of the endogenic earthworm *Pontoscolex corethrurus* on soil chemical characteristics and plant growth in a low-input tropical agroecosystem. *Soil Biology & Biochemistry* 28: 801-810.
- Rossi J-P, 2003. The spatiotemporal pattern of a tropical earthworm species assemblage and its relationship with soil structure. *Pedobiologia* 47: 497-503.
- Spain AV, Lavelle P, Mariotti A, 1992. Stimulation of plant growth by tropical earthworms. *Soil Biology & Biochemistry* 102: 1629-1633.
- Scheu S, 2003. Effects of earthworms on plant growth: patterns and perspectives. *Pedobiologia* 47: 846-856.
- Tondoh EJ. and Lavelle P, 1997. Effect of two organic residues on growth and cocoon production of the earthworm *Hyperiodrilus africanus* (Eudrilidae). *European Journal of Soil Biology* 33: 13-18.
- Tondoh EJ, 1998. Effect of coffe residues on reproduction of *Hyperiodrilus africanus* (Oligochaeta, Eudrilidae) in Ivory Coast. *Biology & Fertility of Soils* 26: 336-340.
- Tondoh EJ, Lavelle P, 2005. Population dynamics of *Hyperiodrilus africanus* (Oligochaeta, Eudrilidae) in Ivory Coast. *Journal of Tropical Ecology* 21: 1-8.
- Tondoh EJ, Monin ML, Tiho S, Csuzdi C, 2007. Can earthworms be used as bio-indicators of land-use perturbations in semi-deciduous forest? *Biology & Fertility of Soils* 43: 584-592.
- Uvarov AV, 2009. Inter- and intraspecific interactions in lumbricid earthworms: their role for earthworm performance and ecosystem functioning. *Pedobiologia* 53: 1-27.
- Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mkwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd KD, Smaling EMA, Woomer PL, Sanginga N, 2010. Integrated soil fertility management. Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture* 39: 17-24.
- Vanlauwe B. and Giller KE, 2006. Popular myths around soil fertility management in sub-Saharan; Africa. *Agriculture, Ecosystems & Environment* 116: 34-46.
- Vinota SP, Parthasarathi K, Ranganathan LS, 2000. Enhanced phosphatase activity in earthworm casts is more of microbial origin. *Current Sciences* 79: 1158-1159.
- Wan JHC. and Wong MH, 2004. Effects of earthworm activity and P-solubilizing bacteria on P-availability in soil. *Journal of Plant Nutrition & Soil Sciences* 167: 209-213.
- World Soil Base for soil resource 2006. World Soil Resources reports, 103. A framework for international classification, correlation and communication. FAO, 127 p.