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RESEARCH ARTICLE

Decomposition, N contribution and soil organic matter balances of crop residues and vermicompost in maize-based cropping systems in southwest Mexico

D. Flores-Sánchez[1,2*], A. Pastor[2], W.A.H. Rossing[2], M.J. Kropff[3] and E.A. Lantinga[2]

*[1]Colegio de Postgraduados, Montecillo, Edo de Mexico, CP 56230, Mexico; [2]Farming Systems Ecology Group, Wageningen University, 6700 AN Wageningen, Netherlands; [3]Crop and Weed Ecology Group, Wageningen University, 6700 AK Wageningen, Netherlands. *Corresponding author: dfs@colpos.mx*

Abstract

Soil fertility depletion is one of the main concerns of the farmers in the Costa Chica, Mexico. The current crop management exacerbates nutrient cycling unbalances and threatens the sustainability of the common maize production systems. It is necessary to supply the soil with organic sources. Field experiments were established in farmers' fields to estimate the decomposition rate and N release of organic materials: aboveground and belowground plant residues, and vermicompost. Decomposition was monitored using the litterbag method, and decomposition patterns were fitted by means of a dynamic mono-component mineralization model. To calculate the effects of crop residues retention and vermicompost on OM balance, five scenarios were evaluated with farm DESIGN model. The decomposition rate was greater during the first 4 months. After that period the remaining dry matter proportion of aboveground residues varied between 45 and 67%. In case of root residues, the dry weight loss ranged between 20 and 47% after the first month. For both types of residues, N released within the first month was 37%, on average. At the end of the sampling period 9 months, the remaining dry matter proportion of aboveground and belowground residues ranged from 30 to 55%, whereas more than 80% of their total N was released. After 6.5 months only 35% of the vermicompost mass was decomposed, but about 65% of its N was mineralized. Besides, around 70% of the vermicompost N was released during the first 30 days. In fields with vermicompost maize was responsible for 70% of total N uptake, on average. The N balance was 93% higher than maize fields without vermicompost. In scenario with 30% of crop residue retention along with vermicompost, OM balance was 86% higher than under current management. Vermicompost can be regarded as an attractive amendment for both crop N supply and soil organic matter build-up.

Keywords: Crop residues, vermicompost, decomposition rate, N release, mineralization model, SOM balance

1. Introduction

Agriculture production faces a number of challenges linked to global population growth and increasing demand for food (Dufumier, 2010). One of the main threats is soil degradation which affects about 2 billion hectares worldwide with severe consequences for food security, ecosystems services, agroecosystems resilience and climate change (Lal, 2009). The main challenges are restoring and improving soil quality. Sustainable management practices of soils through the application of organic materials such as crop residues, compost and green manures can maintain or increase soil organic matter (SOM) (Govaerts *et al*., 2009). In general crop residues are the most readily available source of organic matter (Kumar y Goh, 2000). It is estimated that about 74 Tg of crop residues are annually produced worldwide (Kim and Dale, 2004), and they are an important source of macronutrients (N, P, K) (Kumar y Goh, 2000). Crop residue management and its decomposition have become an important issue and a key process to restore and improve soils (Turmel *et al*., 2015). Nutrient release from crop residues and its cycling have influence on crop yield, and can reduce the needs of external inputs such as mineral fertilizers (Kamkar *et al.*, 2014).

In Mexico, around 80% of agricultural soils are degraded (SEMARNAT, 2013) which is attributed to monocultures, land use change, intensive farming, amongst other factors It is estimated that 77.7 million t yr^{-1} of crop residues are produced annually. Maize crop residues contribute with 48.1 million t yr^{-1}, and 60% is used for feeding animals (Améndola *et al*., 2006).

In the region of the Costa Chica, Mexico, farming systems are organized in small production units with land holdings ranging from 1.5 to 9 ha. The main crops are maize (*Zea mays* L.) and roselle (*Hibiscus sabdariffa* L.). Soil fertility decline is one of the main concerns of the farmers. Chemical fertilizers constitute the main input for crop nutrition, and only few farmers use animal manure. Besides, manure is usually applied only to the fields close to the homestead. Main sources of organic matter to be returned to the soil are the crop residues which are left at the end of the growing season.

However, currently these are mainly grazed by animals roaming the fields unprotected by fences during the dry season. Additional inputs of organic materials such as vermicompost are therefore necessary under these poor soil fertility conditions to restore soil organic matter (SOM) and to improve physico-chemical soil properties like soil pH (Flavel and Murphy, 2006). At the same time, these sources of organic material can reduce soil erosion in the region which is a major problem due to the hilly landscape and the intensive rainfall during the growing season. In one of the municipalities of the Costa Chica, Tecoanapa, was established a vermicomposting facility aimed to have another option for crop nutrition and a mean to alleviate soil degradation. However, in the Costa Chica, no information exists on the role of decomposition of and nitrogen (N) release from crop residues and vermicompost that would allow improving the nutrient use efficiency in the smallholders' maize-based cropping systems. Here we report experiments carried out on farmers' fields during one growing cycle to evaluate i) the decomposition and N release pattern of aboveground and root residues of maize and weeds, and of vermicompost which attracts increasing attention in the region, ii) N uptake by maize and weeds from these organic materials and mineralized soil N by means of an N balance and iii) SOM balances at farm level.

2. Materials and Methods

Experimental sites

Two on-farm experiments were conducted in two communities of the municipality of Tecoanapa (16°48' N, 99°09'), Guerrero, Mexico during the growing season of 2007. Mean annual temperature was 27 °C, and precipitation was 1822 mm. Soils were classified as Loamy Eutric Regosols (SEMARNAT, 2013). Two experimental sites were selected to carry out the study: field JR located in the village of Xalpatlahuac and field IM located in the village of Las Animas. The first field was characterized as fertile on a steep slope with a loamy texture and cattle could roam freely after maize harvest. The second field was flat and less fertile with a loamy-sandy texture and fenced to prevent grazing (Table 1).

Experimental procedures

The trial was part of a larger experiment in which maize was grown with different sources of nutrients (vermicompost, chemical fertilization NPK, vermicompost + chemical fertilization NPK) and an unfertilized control. The experimental design was a complete randomized block with three replicates of each treatment. The decomposition and N release was carried out in the 5 m × 5 m unfertilized maize plots. Individual plots comprised five rows of 5 m at a between row spacing of 1 m. The planted maize cultivar was the criollo locally known as Palmeño. Sowing was carried out in the last week of June. Herbicide (1 L ha^{-1}) was sprayed one week before sowing and three weeks after sowing. Maize was harvested in the first week of November. To estimate N, and soil organic matter (SOM) balances aboveground biomass of maize and weeds were estimated in plots fertilized with vermicompost (10 t ha^{-1}) and in the unfertilized plot. Maize plants from the central row but excluding border plants were cut at ground level and separated into grains and stover, while weed biomass was sampled in a subarea of 1 m^2 within the central row. Plant material was oven-dried at 70 °C for 24 hours to estimate aboveground dry matter production. Maize grains, maize stover and weeds were analyzed for N, P and K. Total N was analyzed using the semi-micro-Kjeldahl procedure. Total aboveground maize and weed N uptake were used to construct field N balances.

Table 1. General soil properties of the two experimental fields

Field	Exp.	Slope (%)	pH (H_2O)	O.M.	Org. C	Nt	P Bray $^{-1}$ mg kg^{-1}	K cmol kg^{-1}	Sand	Clay	Silt	Bulk density g cm^3	Field capacity	Per-manent wilting point
				g kg^{-1}					(%)				(%)	
IM	M-2	5	4.3	11	6.4	0.4	15	0.30	51	21	28	1.38	14.9	7.4
JR	M-3	21	3.7	13	7.5	0.5	18	0.63	40	23	37	1.44	22.9	8.6

Sampling of organic materials

Aboveground residues

Aboveground maize crop and weed residues were sampled in April 2007. Five areas of 1 m^2 were randomly selected in each field. Aboveground maize crop residues were separated in stems and leaves, and the proportion of weeds in the sampled material was measured before drying. The plant material was oven-dried at 70 °C for 24 hours and total aboveground biomass was estimated (kg DM ha^{-1}). The initial N, P and K content (g DM ha^{-1}) in aboveground crop residues for IM field was 9.1, 0.2, and 0.9, respectively. In JR field, N, P and K content g DM ha^{-1}) was 9.4, 1.1 and 2.6, respectively.

Root residues

The belowground biomass was estimated in April 2007. Five columns (monoliths) of 0.2 m × 0.2 m × 0.2 m were dug from the field and transferred to the lab. Monoliths were soaked with water, and roots were carefully removed. Roots were oven-dried at 70 ^{o}C for 48 hours and weighed. The initial N, P and K content (g DM ha^{-1}) in roots for IM field was 10.7, 0.4 and 0.9, respectively. In JR field N, P and K content (g DM ha^{-1}) was 10.9, 1.5 and 4.2, respectively.

Vermicompost

The vermicompost was produced and provided by the Center of Agricultural Technological Baccalaureate No. 191 located in Tecoanapa, Mexico. The facilities to produce vermicompost consisted of 10 compost beds made of bricks and cement with a slight slope (1-2%). Each bed was enclosed by a wall (1 m × 10 m × 0.5 m). Substrate consisted of a mixture of dry crop residues, grass hay, leaves of trees, and cattle manure (mainly goat manure) in a ratio of 25% dry plant residues and 75% cattle manure. The substrate was carefully mixed and watered in order to start the composting process and covered with straw. After three weeks, about 10 cm of the substrate was put in the compost beds and stocked with about 1000 earthworms (*Eisenia foetida*) per square meter. The substrate was covered with a mesh in order to reduce moisture loss and to protect earthworms from birds. Every two weeks another layer of 10 cm of substrate was applied until a final height of 40 cm height was formed. Water was sprinkled every three days to maintain moisture content and to regulate the body temperature of the earthworms. Three months after starting the procedure the vermicompost was collected and sieved through a 1 cm mesh size. Average moisture content was 40%. N, P and K content (g DM ha^{-1}) in vermicompost was 9.3, 2.4 and 7.9, respectively

In all the organic materials total N was analyzed using semi-micro-Kjeldahl procedure. P and K were analyzed by inductively coupled plasma spectrometry (ICP-AES Varian Liberty Series II, Varian Palo Alto, CA, USA).

Litterbag preparation and processing

Decomposition of the organic materials and N release was studied during the rainy season using the litterbag method (Beyaert and Fox, 2008). Litterbag is a standardized method, widely used in different ecosystems and agroecosystems to estimate experimental decomposition rates and nutrient measurements of organic substrates such as leaf litter and recalcitrant materials (e.g. litter, crop residues, roots, manure, compost and vermicompost) (Coleman *et al*., 2004; Rasse *et al*., 2005; Kara *et al*., 2014). The organic substrates are enclosed in mesh bags with appropriate mesh sizes and laid on the soil surface or buried in the soil (Wieder and Lang, 1982). Litterbags are then collected on a time schedule and the remaining mass is measured (Coleman *et al*., 2004),

and the decomposition rate is determined (Rasse *et al*., 2005). The resulting decomposition rates show trends of decomposition, and allow for comparisons among species, sites, and experimental manipulations (Karberg *et al*., 2008).

Aboveground residues

Nylon litterbags of 30 cm × 25 cm (2 mm mesh size) were filled with 50 g DM of aboveground crop and weed residues, amount that fit well inside the bags. The size of litterbags was within the common size used for these studies (Karberg *et al*., 2008). This mesh size was selected to ensure close contact among the biotic environment (micro- and meso-fauna, bacteria and fungi), the abiotic soil surface and the crop residues in the litterbag (Bradford *et al*., 2002). In field JR the bags were randomly placed on the soil during the first week of May, while in field IM this was done in the third week of May; 12 bags were used per location. In field JR, bags were recovered after 6, 17, 26 and 38 weeks, and in field IM after 4, 14, 23 and 34 weeks.

Root residues

The root residues were put in 12 nylon bags of 10 cm × 15 cm (40 µm mesh size). The litterbags were smaller than those of crop residues. Roots were relatively found in low amounts and in small sizes what made little practice used the same size of litterbags used for crop residues. The bags were filled with 10 g DM of root residues, amount that fit well within the bag. The chosen mesh size was small in order to avoid losses from litterbags as well as to prevent exchange with soil particles and debris (i.e. excluding the influence of meso-fauna), but allowing contact with micro-fauna, bacteria and fungi (Bradford *et al*., 2002). The bags were buried horizontally at a depth of about 10 cm under the soil surface in each field during the first week of July. The bags were retrieved after 8, 17 and 29 weeks for field JR and at 7, 11 and 28 weeks after placement for field IM.

Vermicompost

Vermicompost was added in 12 nylon bags of 10 cm × 15 cm (40 µm mesh size) at a rate of 37.5 g DM per bag, amount that fit well in the bag. The small size of the mesh was selected to avoid loss of material through the mesh, and to prevent soil contamination. However, it excludes the effects of meso and macrofauna. The vermicompost bags were buried horizontally at 10 cm below the soil surface. In field JR, bags were buried during the last week of June, and sampling occurred 5, 13, 16 and 21 weeks after placement. In field IM the bags were placed in the first week of July and sampling took place 4, 11 and 28 weeks after installation.

Samples collection and analyses

Three replicates of each group of organic materials were randomly harvested at each sampling time. The plant residues were carefully separated from the bags and sprinkled with water to remove adhering soil. The remaining materials were oven-dried in small aluminum containers at 70 ^{o}C for 48 h, and weighed. Total N in the samples was determined by the semi-micro-Kjeldahl procedure. In case of the aboveground residues, about 25% of the material contained in the bags was taken for the analysis, while in case of roots and vermicompost all of the material contained in the bags was analyzed.

Modelling material and nitrogen decomposition patterns and statistical analysis

The decomposition patterns of the organic materials were calculated using the mono-component mineralization model developed by Yang and Janssen (2000) in which the organic matter dynamic is treated as a single component over time. The mineralization rate, K (t^{-1}), is calculated as:

$$K=Rt^{-S} \quad (1)$$

Where R (dimension t^{S-1}) represents K at t=1, and S (dimensionless, $1 \geq S \geq 0$) is a measure of the rate at which K decreases over time.
The amount of remaining organic material on time t (Y_t), is calculated by:

$$Y_t=Y_o \exp(-Rt^{1-S}) \quad (2)$$

Where Y_o is the initial quantity of the organic material.

The model parameters R and S in Equation 2 were fitted using the non-linear regression procedure in PASW Statistics 17.
Two methods were used to the estimate the potential soil supply of N (SN; kg N ha^{-1}). The first method was proposed by Janssen *et al*. (1990):

$$SN = fN * 6.8 * C \quad (3)$$

$$fN = 0.25 * (pH-3) \quad (4)$$

Where C represents soil organic carbon (g kg^{-1}), assuming 58% C in SOM, and pH is pH (H_2O); for the calculations a minimum value of 4.5 was assumed.

Statistical analysis

An analysis of variance was used to test the difference in remaining biomass and N in each organic material per sampling date. Means separation was done when the F-test indicated significant ($P<0.05$) differences using Tukey's studentized range HSD test. Statistical analyses were performed with SPSS V.22.

Nitrogen balance

The N balance of the two fields was calculated as the difference between the combined N release from soil and organic materials on the one hand and N uptake by maize and weeds on the other. In both fields N balanced was calculated in plots with vermicompost and unfertilized plots (control).

Organic matter balance

Organic matter balance was estimated by means of the Farm DESIGN model (Groot *et al*., 2012). The model calculates transfers of OM between the farm components: crops, animals, manure and soil, all based on production ecological relations.
The OM balance was calculated by combining four 'sub-balances': root residues, aboveground crop residues, vermicompost and soil OM. Balances were calculated as the difference between annual input and output. In both fields five scenarios were evaluated: 1) current practice. It was based on the amount of crop residues found during sampling; 2) vermicompost + 30% crop residue retention; 3) vermicompost + 100% crop residue retention; 4) without vermicompost + 30% crop residue retention; 5) without vermicompost + 100% crop residue retention.

The net contribution of root and aboveground crop residues (obtained from litterbag experiments) to the OM balance in each experimental plot was quantified as the amount of OM remaining one year after application in the field (Groot *et al*., 2012). Root biomass was estimated as 15% of total crop biomass (Rodríguez, 1993). Decomposition rate of aboveground residues, root residues and vermicompost were taken from our litterbag experiments.

3. Results

Parametrization of the mono-component model

The mono-component model was parameterized for the three organic materials in each field (Tables 2 and 3). The parameter values for R and S presented in Table 2 demonstrate major variation in OM decomposition among the materials.

Table 2. Fitted parameter values R (±SE) and s (±SE) for OM decomposition of the three groups of organic materials in the two fields according to the mono-component model.

Field	Organic material	R (year s^{-1})	s	r^2 adjusted
IM	Aboveground residues	0.79 (± 0.07)	0.41 (± 0.08)	0.94
	Root residues	1.11 (± 0.26)	0.41 (± 0.18)	0.84
	Vermicompost	0.48 (± 0.03)	0.89 (± 0.03)	0.98
JR	Aboveground residues	2.10 (± 0.39)	0.03 (± 0.19)	0.89
	Root residues	0.83 (± 0.37)	0.86 (± 0)	0.98
	Vermicompost	0.52 (± 0.06)	0.80 (± 0.08)	0.95

Table 3. Fitted parameter values R (±SE) and s (±SE) for N decomposition of the three groups of organic materials in the two fields according to the mono-component model.

Field	Organic material	R (year s^{-1})	s	r^2 adjusted
IM	Aboveground residues	2.53 (± 0.11)	0.33 (± 0.03)	0.99
	Root residues	3.25 (± 0.18)	0 (± 0.04)	0.99
	Vermicompost	1.35 (± 0.02)	0.71 (± 0.01)	0.99
JR	Aboveground residues	2.65 (± 1.48)	0 (± 0.42)	0.80
	Root residues	2.29 (± 0.16)	0.56 (± 0.05)	0.99
	Vermicompost	1.67 (± 0.05)	0.56 (± 0.02)	0.99

However, differences between fields were only observed for the aboveground plant residues. In case of N disappearance there was hardly any variation among materials and between fields (Table 3). Decomposition patterns were satisfactorily fitted with the model (Figures 1 and 2).

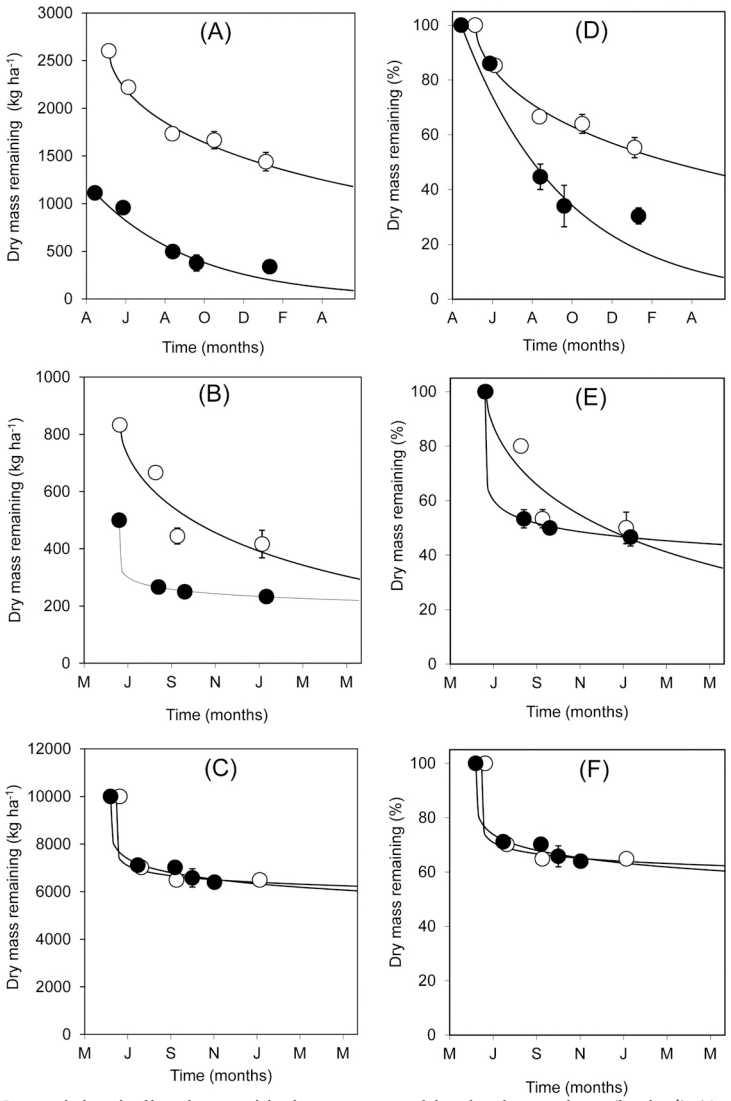

Figure 1. Total DM remaining in litterbags with time expressed in absolute values (kg ha^{-1}) (A, B, C) and as percentages (D, E, F) for the three organic materials in the two fields during the growing season of 2007. (A) and (D) aboveground residues; (B) and (E) root residues; (C) and (F) vermicompost. Open symbols: field IM. Closed symbols: field JR. Solid lines represent the fitted mono-component model. Bars represent standard error of the mean. In some points bars are not visible due to SE value was too small.

Results from the analysis of variance (ANOVA) demonstrated significant difference (P<0.05) among sampling date for each organic material (Table 4). For biomass decomposition the main difference was found between the first and the second sampling. Subsequent samplings were statistically similar among them. In case of N release, the general trend showed significant difference (P<0.05) among samplings for the three organic materials.

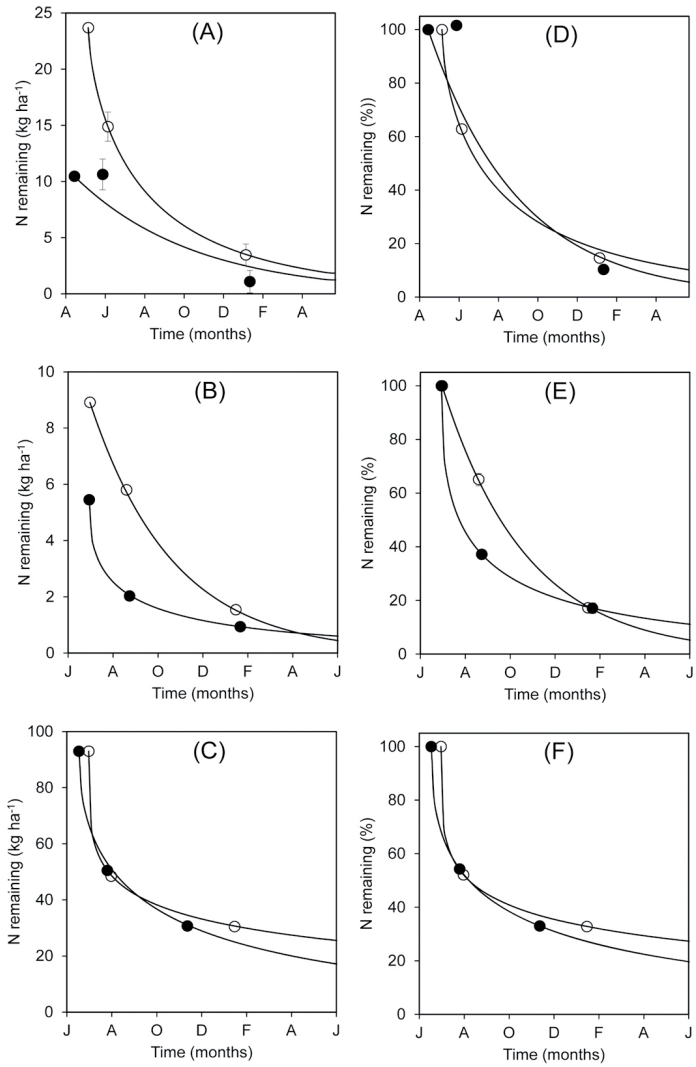

Figure 2. Total N remaining in litterbags with time expressed in absolute amounts (kg ha^{-1}) (A, B, C) and as percentages (D, E, F) for the tree organic materials in the two fields during the growing season of 2007. (A) and (D) aboveground residues; (B) and (E) root residues; (C) and (F) vermicompost. Open symbols: field IM. Solid symbols: field JR Solid lines represent the fitted mono-component model. Bars represent standard error of the mean. In some points bars are not visible due to SE value was too small.

Table 4. Mean (±SE) biomass and N release (kg ha^{-1}) of organic materials per sampling in the two fields. Different letters indicate significant (P<0.05) differences.

Field	Sampling	Aboveground residues	Root residues	Vermicompost	Aboveground residues	Root residues	Vermicompost
IM	1	2603.3 a (± 0)	833.0 a (± 0)	10000.0 a (± 0)	23.7 a (± 0)	8.9 a (± 0)	93.0 a (± 0)
	2	2221.5 b (± 46)	666.7 b (± 0)	7022.2 b (± 89)	14.9 b (± 0.31)	5.8 b (± 0)	48.5 b (± 0.61)
	3	1733.6 c (± 60)	444.4 c (± 28)	6488.9 c (± 178)	3.5 c (± 0.23)	1.5 c (± 0.18)	30.5 c (± 0.42)
	4	1666.1 c (± 90)	416.6 c (± 48)	6488.9 c (± 89)			
	5	1440.5 c (± 97)					
JR	1	1113.3 a (± 0)	500.0 a (± 0)	10000.0 a (± 0)	10.5 a (± 0)	5.5 a (± 0)	93.0 a (± 0)
	2	957.5 a (± 13)	266.7 b (± 17)	7111.1 b (± 89)	10.6 a (± 0.14)	2.0 b (± 0.13)	50.5 b (± 0.63)
	3	497.3 b (± 52)	250.0 b (± 0)	7022.2 b (± 89)	1.1 b (± 0.10)	0.9 c (± 0.07)	30.7 c (± 0.74)
	4	378.7 b (± 84)	233.3 b (± 17)	6577.8 b (± 387)			
	5	338.0 b (± 33)		6400.0 b (± 154)			

Decomposition of organic materials

Aboveground residues

The total amounts of aboveground plant residues measured in April 2007 were 2600 and 1100 kg DM ha^{-1} in fields IM and JR, respectively (Figure 1A). The proportion of weeds in the collected material was 20 and 17%, respectively. The decomposition rate was greater during the first four months. At the end of this period, 67 and 45% of the initial weight remained in fields IM and JR, respectively (Figure 1D). At the end of the sampling period (36 weeks on average) the residual dry mass had declined to 55 and 30%, respectively.

Root residues

Total root biomass measured in April 2007 was 833 and 500 kg DM ha^{-1} for fields IM and JR, respectively (Figure 1B). The initial root DM decomposition rate differed between fields. The loss of weight during the first two months in field JR was 47%, whereas it was only 20% in field IM. However, at the last sampling date in January 2008 these differences had disappeared, and the remaining root biomass in each field was then just below 50% of the amount applied (Figure 1E).

Vermicompost

An application rate of 10 t DM ha^{-1} of vermicompost was taken as the initial amount to estimate the time patterns of decomposition and N release. Decomposition rates followed the same trend in each field (Figure 1C). Within the first 30 days rapid decomposition was observed and about 30% of the initial amount of vermicompost disappeared from the litterbags. After that period decomposition slowed down and at the end of the measuring period the proportion of vermicompost DM that remained was approximately 64% in each field (Figure 1F).

Nitrogen decomposition

Aboveground residues

The initial amount of N in aboveground plant residues was 24 N kg ha^{-1} in field IM and 11 kg N ha^{-1} in field JR (Figure 2A). At the end of the study 9 kg N ha^{-1} was released in field JR (89% of total N applied;

Figure 2D). In field IM this amount was already released within the first 30 days and at the end of the experiment 20 kg N ha^{-1} had been released (85% of total N applied; Figure 2D).

Root residues

The time patterns of remaining N in the root residues are presented in Figures 2B and 2E. The total amount of N at the beginning of the study was 9 kg N ha^{-1} in field IM, and 5.5 kg N ha^{-1} in field JR. Residual N decreased gradually to 1.5 kg ha^{-1} in field IM and 1 kg ha^{-1} in field JR, equivalent to an N-release of 83% in each field (Figure 2E).

Vermicompost

The application rate of 10 t ha^{-1} of vermicompost corresponded with an initial N amount of 93 kg ha^{-1}. Within the first 30 days the N release was 43 kg N ha^{-1} in field JR and 45 kg N ha^{-1} in field IM (Figure 2C), equivalent to an average fraction released of 47%. At the end of the measurements total N release in each field appeared to be 62 kg N ha^{-1} (67% of total N; Figure 2F).

N balance

The estimated soil N supply was obtained by means of the procedure proposed by Janssen *et al*. (1990) the soil N contribution was 16 and 19 kg N ha^{-1} for fields IM and JR, respectively. To construct the N balance the former values were used (Table 4). Total N released during the growing season in plots with vermicompost ranged from 91 to 99 kg N ha^{-1} (Table 5). In the fertilized cropping system this N contribution from vermicompost was on average 63% of the total amount of mineralized N (column 4). In the unfertilized plots, total N release from soil, crop and roots residues ranged between 30 and 41 kg ha^{-1} N contribution from the indigenous organic materials differed greatly between both fields.

Table 5. N balance of the two fields during the growing season of 2007.

Field	N released (kg N ha^{-1})						N uptake (kg N ha^{-1}) plots with vermicompost			Balance[d]	N uptake (kg N ha^{-1}) unfertilized plots			Balance[f]
	Soil	AR*	RR	V	T1[a]	2[b]	Maize	Weeds	T3[c]		Maize	Weeds	T4[e]	
IM	16	19	6	58	99	41	48	9	57	42	30	12	42	-1
JR	19	7	4	61	91	30	15	11	26	65	12	12	24	6

*AR: aboveground crop residues; RR: root residues; V: vermicompost

[a] T1: Total N released from soil and the three groups of organic materials (Soil+A+R+V)

[b] T2: Total N released from soil, and aboveground and root residues (Soil+A+R)

[c] T3: N uptake (kg N ha^{-1}) of maize and weeds with vermicompost (maize + weeds)

[d] Balance plots with vermicompost (T1-T3)

[e] T4: N uptake (kg N ha^{-1}) of maize and weeds unfertilized plots

[f] Balance unfertilized plots (T2-T4)

In field IM, crop available N in the unfertilized treatment from this source constituted 61%, while in field JR this was a mere 37%. In plots with vermicompost the total N uptake in both fields was widely variable (column 9). In field JR, weeds were an important component in terms of competition for N with 42% of the total uptake. N balances in the vermicompost plots were very positive for both fields (column 10). There was a surplus of 42 and 65 kg N ha^{-1} for fields IM and JR, respectively. Without vermicompost, field JR had a similar share of N uptake between maize and weeds, while in field IM the maize crop was responsible for 84% of the total N uptake. The N balance in field IM was almost zero, while in field JR there was a calculated surplus of 6 kg N ha^{-1}.

OM balance

The amount of crop residues produced in each field differed significantly. The application of vermicompost in maize cropping systems increased substantially total biomass. It is noteworthy that between both fields there was a similar trend among the evaluated scenarios (Figure 3). In plots with vermicompost the amount of crop residues was 6205 and 2870 kg ha^{-1} for JM and IM, respectively, and in plots without vermicompost was 4150 and 2689 kg ha^{-1} for JM and IM, respectively. There were substantial differences in OM balances. In field IM ranged from 127 to 1874 kg ha^{-1} yr^{-1} and field, JR varied between 2 and 1365 kg ha^{-1} yr^{-1}. Assuming 30% of residue retention without vermicompost (scenario 4), the OM balance (65 kg ha^{-1} yr^{-1}, on average) was 44% lower than current situation (115 kg ha^{-1} yr^{-1}, on average). However, in scenario 5 the average OM balance was 277 kg ha^{-1} yr^{-1}. The inclusion of vermicompost and crop residue retention was an option that increased substantially OM balance. In scenario 2 the OM balance was 874 $ha^{-1}yr^{-1}$, on average, while in scenario 3 it was 1619 kg ha^{-1} yr^{-1}. Both amounts were substantially higher than current management (115 kg $ha^{-1}yr^{-1}$).

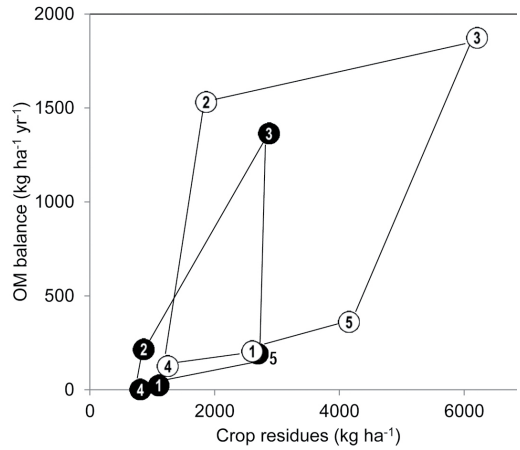

Figure 3. Relationship between crop residue retention (kg ha^{-1}) and OM balance (kg ha^{-1} y^{-1}) for five scenarios on two fields. 1: current, 2: vermicompost + 30% crop residue retention; 3: vermicompost + 100% crop residue retention; 4: without vermicompost + 30% crop residue retention; 5: without vermicompost + 100% crop residue retention. Open symbols: field IM. Solid symbols: field JR.

4. Discussion

In two on-farms litterbag experiments aimed to establish the patterns of mass decomposition and N release of three groups of organic materials the mono-component model appeared to be an appropriate fitting tool. The estimated parameter values for the DM degradation of aboveground plant residues and root residues differed widely between the fields of each of the two farms. However, at the end of the experiment there appeared to be no differences any longer in case of the root residues. The slower breakdown of aboveground

residues on field IM as compared to JR could not be explained from the weed content in these residues because they were almost the same. However, the total amount of aboveground residues was more than twice as high on this field and the P and K contents were much lower compared to those on field JR. This might indicate that the share of less degradable maize stems was higher on the field of farm IM. Since there were no differences between the decomposition patterns of the applied vermicompost on each field this seems to be a plausible explanation. Vermicompost is well-known for its high content of lignin which is a recalcitrant compound with a great resistance to microbial decomposition. In accordance with this is the observation that almost two-thirds of the vermicompost mass was still present in the litterbags of both fields at the end of the experiment.

Concerning both the aboveground and belowground residues the overall level of DM decomposition was higher than that of vermicompost. Even though, the size of litterbags was different for each material, the amounts used in the different substrates did not affect the trend of our results, since similar patterns were observed in the two selected fields. The observed average value of about 50% at maize harvest is in agreement with a number of other experiments carried out over a period of less than one year (Pérez *et al*., 2000; Burgess *et al.*, 2002). This patter is caused by chemical composition of litter types or organic materials (Cepáková and Frouz, 2015).

The N release pattern from the organic materials differed little between the two fields. However, about 70% of the vermicompost N was released during the first 30 days on both locations, whereas initial N decomposition was especially lower in case of root residues. According to the N balances, there were great surpluses when all the organic materials were considered together. This was accompanied by a total aboveground N recovery by the maize crop of 0.2 for vermicompost in field IM, while in field JR this was close to 0. These low values can be partly explained through the relatively high share of weeds in the total N uptake, particularly in field JR, but above all they point into the direction of N immobilization and run-off losses. In acidic soils with a pH around 4, like in the current study, nitrification is inhibited (Harmsen and van Schreven, 1955). Under these conditions ammonification is largely carried out by fungi since bacteria show little activity. Therefore, nitrate leaching losses may not be expected to take place and the assimilated N is incorporated in the pool of living soil biomass (Andrew *et al.*, 2002). As a consequence, soil microorganisms acquire inorganic N before plants, thus greatly reducing the availability of N for maize roots (Hodge *et al.*, 2000). These processes all take place in the top layer of the soil profile which was especially in the slopy field JR very vulnerable to run-off losses. Already in July, the first month of the experiment, the 300 mm of rainfall greatly exceeded the evaporative demand of the vegetation. In August the situation was even worse since then a precipitation of 800 mm was recorded.

The initial N release from the aboveground plant residues as well as from the roots proceeded at a slower rate compared to vermicompost. In the unfertilized plots, where only these residues were present, the N balances were more favourable. It was calculated that the N balance in field IM was close to zero. In the more acidic field JR with a lower level of plant-available N, the N uptake by weeds and especially maize was very restricted. This resulted in an extremely low maize grain yield of 300 kg ha^{-1} and a positive N balance that was equal to 25% of the total amount of N absorbed by the maize and the weed plants. Other studies demonstrated that N derived from maize residues was more essential for N maintenance than as source of N supply for crop production (e.g. Mubarak *et al.*, 2003).

According to our estimations crop residue retention and application of vermicompost increased SOM balances which varied widely between both fields. It was associated with the amount of biomass produced and the inherent fertility of each field.

Inclusion of organic sources is particularly important for sandy soils which are widely distributed in the region of Costa Chica, and characterized by low levels of SOM (Flores-Sanchez *et al*., 2011). Under these conditions the main aim for residue retention is enhancing and maintaining SOM. External organic inputs such as vermicompost demonstrated positive effects on OM balances, and along with its decomposition patterns is a potential external source that allows increasing the SOM stock which is one of the most important factors in soil conservation and reclamation (Bernal *et al*., 1998). However, this option can have trade-offs linked to costs of acquisition, transport and application (Flores-Sánchez *et al*., 2014). It highlights the needs to carry out experimental trials to test various dosage to face these trade-offs.

In our study region, estimations in farmers fields' (data no published) during the middle of dry season (April) demonstrated that soil cover in fields with fences was 57%. The amount of crop residues ranged from 1956 to 3616 kg ha^{-1}. In fields with animal roaming soil cover was 34%, and the amount of crop residues varied between 1130 and 3514 kg ha^{-1}. However, that source of organic matter is not being completely harnessed since at the beginning of the rainy season most of the farmers remove the remaining crop residues, a practice known as "rastrojear", and burn them subsequently in order to facilitate farming practices (Flores-Sánchez *et al*., 2011). Several studies have demonstrated that crop residue retention can be one of the most promising options to enhance SOM particularly in smallholder systems where crop residues are the unique source of organic matter (Rusinamhodzi *et al.*, 2015). The combined use of maize residues and green manures is other promising option that can increase C and N mineralization and improve microbial biomass (Partey *et al*., 2014). SOM accumulation can be reached in the long term through annual crop residue retention, even though they have medium contents of N, lignin, and polyphenols, and low to medium contents of cellulose (Putasso *et al*., 2013).

It is well established the multiple effects of crop residues on soil quality. However, smallholder systems face trade-offs since they can be used for livestock feeding, soil fertility maintenance, or can be removed to facilitate cultural practices (Amendola *et al*., 2006; Blanco-Canqui and Lal, 2009; Tittonell *et al*., 2015). Within this context it is necessary to design and implement strategies on the long-term to use crop residues for both livestock feed and source of organic matter to the soil, and as far as possible include other organic sources (e.g. vermicompost). Some explorations have demonstrated that the use of crop residues for both purposes (feeding animals and retention) and inclusion of vermicompost are feasible options with positive effects on SOM at farm level (Flores-Sánchez *et al*., 2014; Rusinamhodzi *et al*., 2015). These options should be a component of any soil restoration strategy which is an essential issue for long-term productivity, and to increase resilience to climate chance (Lal, 2009).

5. Conclusions

Over one growing season it was observed that the remaining aboveground crop and weed residues presented higher variation in the degree of decomposition (from 30 to 55%) between both fields than roots and vermicompost. This difference was in all probability due to a more stemmy nature of the maize residues in one of the fields. On average, about 50% of the total residues were decomposed and nearly all of their N was released from the litterbags. The remaining vermicompost appeared to be the least decomposed material.

However, due to its much higher N input level the N contribution was higher than from aboveground maize and weed residues and roots together. Vermicompost can therefore be considered as a promising option to increase soil organic matter turnover and improve crop production. However, it is necessary to adjust its application strategy by synchronizing nutrient release with crop demand. Most of the vermicompost N is released during the first weeks of the growing season when there is a great risk that rainfall exceeds evapotranspiration. Crop residue retention along with vermicompost can be a promising option to improve OM balances. Assuming 30% of crop residue retention, OM balance was 86% higher than current management. The use of vermicompost as source of maize nutrition increase N uptake by 93% compared with maize fields without vermicompost. Further studies are recommended to evaluate decomposition of organic materials and N release patterns for periods longer than one year in order to quantify the system N dynamics in subsequent years. Besides, it is worthwhile to gain more insight in the process of N capture by microorganisms in relation with soil pH and the magnitude of run-off losses.

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