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Earthworm populations in relation to soil organic matter dynamics and management in California tomato cropping systems

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ABSTRACT

Earthworms are key regulators of soil structure and soil organic matter (SOM) dynamics in many agroecosystems. They are greatly impacted by agricultural management, yet little is known about how these factors interact to control SOM dynamics. This study sought to explore linkages between agricultural management, earthworms and aggregate associated SOM dynamics through a survey of tomato (*Solanum lycopersicum* L.) cropping systems in northern California. Earthworms and soil samples were collected between February and April of 2005 from 16 fields under one of three types of residue management: (1) tomato mulch – no postharvest tillage and tomato residues left on the soil surface, (2) cover crop – tomato residues tilled in and leguminous cover crop planted, and (3) bare fallow – tomato residues tilled in and soil surface left exposed throughout the winter. Earthworms were collected via hand-sorting and identified to species, while soils were wet sieved to yield four aggregate size classes: large macroaggregates (>2000 μm), small macroaggregates (250–2000 μm), microaggregates (53–250 μm) and the silt and clay fraction (<53 μm). The combined large and small macroaggregate fraction was then fractionated into coarse particulate organic matter (cPOM; 250 μm), micro-aggregates within macroaggregates (mM; 53–250 μm) and macroaggregate occluded silt and clay (Msc; <53 μm). The earthworms identified in this survey were composed entirely of exotic species and were dominated by *Aporrectodea caliginosa*. Earthworm abundance was related to residue management, with the tomato mulch systems averaging 4.5 times greater fresh earthworm biomass than bare fallow ($P = 0.024$). Aggregate stability and total soil C and N also appeared to be influenced by residue management, such that the tomato mulch system displayed significantly greater mean weight diameters than the bare fallow system ($P = 0.049$), as well as more than 50% greater total soil C and N ($P = 0.049$ and $P = 0.036$; respectively). Earthworm biomass was also found to be positively correlated with total soil C ($P = 0.009$, $R^2 = 0.39$) and N ($P = 0.010$, $R^2 = 0.039$) as well as the proportion of macroaggregate C in the cPOM fraction ($P = 0.028$, $R^2 = 0.30$). Our findings suggest that residue handling and the associated management practices (e.g., tillage, organic vs. conventional agriculture) are important for both earthworm populations and SOM storage. Although earthworms are known to influence SOM in many ways, other factors appear to play a more prominent role in governing aggregate associated SOM dynamics.

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1. Introduction

Understanding the influence of agricultural management on soil organisms and their relationship with soil organic matter (SOM) dynamics is imperative for the development of sustainable agroecosystems. Earthworms in particular have gained widespread attention due to their influence on a diverse array of soil processes including aggregation, residue decomposition, nutrient mineralization, aeration, and water infiltration (Lee, 1985). The ability of earthworms to affect soil functioning by such varied mechanisms has earned them recognition as ecosystem engineers (Jones et al., 1994; Lavelle et al., 1997) and has generated much interest in determining the factors that govern their abundance and community composition. In agricultural systems, a number of controls on earthworm growth and survival have been put forth; these include tillage, fertilization, soil C inputs, and soil texture (Kladivko et al., 1997; Chan, 2001; Marhan and Scheu, 2005). Given the diverse means by which earthworms can alter soils, it becomes evident that both earthworms and many of the factors that regulate their populations can dramatically impact SOM dynamics (Paustian et al., 1997; Brown et al., 2000). Improving our knowledge of how these factors interact to influence SOM is thus pertinent to advancing the responsible management of agricultural systems.

Soil organic matter is fundamental to the long-term sustainability of agroecosystems and plays a critical role in global biogeochemical cycles (Tiessen et al., 1994; Lal, 2004). Extensive research on organic matter dynamics in agricultural soils and the influence of management has focused on the relationship between SOM and soil structure. SOM is a key driver of soil aggregation and is in turn influenced by its distribution among different aggregate size fractions (Lal, 2000; Six et al., 2002). SOM stored within aggregates often represents the vast majority of carbon within soils. However, differences in binding mechanisms between aggregates of different size classes results in varying degrees of aggregate stability, such that the susceptibility of aggregate-associated SOM to management induced losses often depends on the size of the aggregates (Tisdall and Oades, 1982). Microaggregates (53–250 μm) are thought to slow the turnover of SOM, withstand disturbance and protect C more effectively than macroaggregates (>250 μm) (Angers et al., 1997; Six et al., 2002). However, the contribution of macroaggregates as a site for the formation of stable microaggregates (Six et al., 2000) indicates the need to consider aggregates of multiple size classes when assessing management impacts on SOM stabilization.

Although the overall influence of earthworms on SOM remains inconclusive (Brown et al., 2000), several studies have shown that earthworms may act to stabilize soil C by rapidly incorporating organic residues into microaggregates within macroaggregates (Bossuyt et al., 2004; Pulleman et al., 2005; Fonte et al., 2007). These newly formed microaggregates protect organic matter from decay, even after the breakdown of the macroaggregates in which they are formed, and thus represent a mechanism for the stabilization of SOM (Six et al., 2000; Bossuyt et al., 2005). Management can thus influence SOM by affecting aggregation directly, or indirectly via alterations to earthworm populations and their subsequent contribution to soil structure. This suggests that consideration of both direct impacts and less straightforward mechanisms are required for improved understanding of management impacts on SOM dynamics.

The objective of this research was to investigate relationships between agricultural management, earthworms and aggregate-associated SOM by measuring soil properties and earthworm populations across a range of farms under varying management practices. We hypothesized that management, particularly residue handling and tillage, would influence earthworm populations and activity. Furthermore we aimed to test the hypothesis that earthworms increase SOM stabilization within soil aggregates.

2. Materials and methods

2.1. Site description

Sampling was conducted in 16 agricultural fields located in Yolo and Solano Counties, in the western Sacramento Valley of California. This region experiences a Mediterranean climate with an average annual rainfall of roughly 500 mm year^{-1}. The summer growing season generally lasts from April to October, but irrigation and mild winter temperatures allow for near continuous plant growth and earthworm activity. Soils ranged from sandy loam to clay dominated soils (see Table 1).

2.2. Management information

All fields were under organic or conventional tomato (*Solanum lycopersicum* L.) production during the 2004 summer growing season. Field management data was collected at each site through observation and farmer interviews where possible. Collected information included: timing and intensity of tillage, types of fertilizers applied, residue management, form of irrigation, and years under organic farming (Table 1). Residue management consisted of three basic categories: (1) tomato residues left on the soil surface with no postharvest tillage (tomato mulch; $n = 7$), (2) residues tilled into the soil and a cover crop planted (cover crop; $n = 5$), or (3) residues tilled in and the soil surface left bare (bare fallow; $n = 4$). Although a number of factors are known to influence earthworms and SOM dynamics, this study places emphasis on residue management. Representing the most obvious grouping of management systems at the time of sampling, residue management serves as an integrative variable, embodying management differences associated with tillage, irrigation and overall farm management (see Table 1).

2.3. Earthworm sampling and identification

Field sampling occurred between February and April of 2005, when conditions were optimal for earthworm activity (i.e., soil moisture was sufficiently high and temperatures were beginning to rise). Within each field, three replicate pits (30 cm $\times$ 30 cm $\times$ 30 cm) were rapidly excavated in the center of pre-existing beds and within close proximity of each other (<10 m). Earthworms were removed by hand-sorting and returned to the lab for identification and weighing. Prior to

Table 1 – Management and site information for 16 fields sampled in Yolo and Solano Counties between February and April 2005.

Farm	Residue management	Location	Soil texture[a]	System type	Irrigation type	Tillage intensity[b]	Time organic[c]	Nutrient amendments
Site 1	Tomato mulch	Rumsey	60/23/17	Organic	Drip	8	>30	Gypsum, blood + bone meal
Site 2	Tomato mulch	Capay	54/31/14	Organic	Drip	6	12	Fish meal, P
Site 3	Cover crop	Esparto	17/41/42	Organic	Drip	7	14	Chicken manure, guano, gypsum, sulfur
Site 4	Tomato mulch	Dixon	21/45/34	Organic	Drip	5	5	Compost
Site 5	Tomato mulch	Winters	30/44/26	Organic	Drip	7	20	Guano, blood meal, fish emulsions
Site 6	Bare fallow	Woodland	21/46/32	Conventional	Furrow	7	0	Inorganic N, P, S
Site 7	Cover crop	Woodland	27/46/27	Organic	Furrow	10	5	Guano
Site 8	Tomato mulch	Guinda	40/35/26	Organic	Drip	3	20	Compost, organic fertigation[d], gypsum
Site 9	Cover crop	Guinda	35/36/29	Organic	Drip	4	5	Compost, gypsum, organic fertigation
Site 10	Bare fallow	Woodland	26/46/28	Organic	Drip	9	9	Inorganic N, P, K, S, Ca
Site 11	Tomato mulch	Guinda	27/45/28	Organic	Drip	5	9	Compost, organic fertigation, feather meal, fish emulsions
Site 12	Bare fallow	Winters	36/35/29	Conventional	Furrow	8	0	Inorganic N, P, K, S
Site 13	Cover crop	Winters	31/37/31	Organic	Furrow	9	13	Turkey manure, grape pumice
Site 14	Tomato mulch	Davis	56/27/17	Organic	Drip	4	30	Compost
Site 15	Bare fallow	Winters	19/39/42	Conventional	Drip	6	0	Inorganic N
Site 16	Cover crop	Winters	14/32/55	Organic	Drip	9	3	Turkey manure

[a] Soil texture numbers represent percentages of sand/silt/clay.
[b] Tillage intensity is defined as number of soil penetrating passes in year prior to sampling.
[c] Continuous time (years) since field has not been under conventional agriculture.
[d] Fertigation refers to the application of soluble organic nutrients through drip irrigation.

refilling the excavated pits, soil below 30 cm was examined for earthworm tunnels to assess the presence of deeper burrowing species. In the lab, earthworms were separated into sexually mature adults (with fully developed clitellum), preclitellate individuals, earthworm fragments, and cocoons. All worms, fragments and cocoons were cleaned in water and patted dry with a paper towel for determination of fresh biomass. Mature specimens were anesthetized in a diluted ethanol solution and identified according to Sims and Gerard (1999).

2.4. *Soil sampling*

Soil samples (0–15 cm) were removed from the side of each earthworm pit after gently scraping away vertical sections of soil that may have been compacted by digging. Bulk density and soil moisture were determined using cylindrical cores inserted horizontally into a wall of each pit. All soil samples were placed in cold storage immediately following collection and returned to the lab for subsequent analyses.

2.5. *Soil analyses*

Upon return to the lab, field moist soils were passed through an 8 mm sieve by gently breaking soil clods along natural planes of fracture and then air-dried. A sub-sample of this soil was removed for determination of soil texture by the hydrometer method (Sheldrick and Wang, 1993).

Additional sub-samples (60 g) of the air-dried soils were wet-sieved following methods described by Elliott (1986). Briefly, soil was placed on a 2 mm sieve and slaked by submerging it in deionized water for 5 min before sieving. The sieve was then gently oscillated by hand in an up and down motion for a total of 50 cycles over a 2 min period. Material remaining on the sieve was rinsed into a pre-weighed aluminum pan, while material passing through the 2 mm mesh was transferred to a 250 μm sieve for further fractionation. The sieving process was repeated with both a 250 μm and a 53 μm sieve, ultimately generating four fractions: large macroaggregates (>2 mm), small macroaggregates (250–2000 μm), microaggregates (53–250 μm) and silt and clay (<53 μm). After sieving, all fractions were oven-dried at 60 °C and weighed. Due to the small percentage of large macroaggregates in several of the soils, large and small macroaggregates were combined for subsequent analyses. Aggregate stability was assessed using mean weight diameter and was calculated following van Bavel (1950) by summing the weighted proportion of each aggregate fraction present in a whole sample of soil.

The combined macroaggregate fraction was separated according to Six et al. (2000). In short, 10 g of oven-dried macroaggregates were slaked in deionized water for 30 min. These samples were then gently shaken with 50 stainless steel bearings (4 mm diameter) while submerged on top of a 250 μm mesh screen until all macroaggregates were broken. A continuous stream of water flushed the <250 μm material through the mesh in order to avoid the breakup of microaggregates released from the macroaggregates. Further sieving of the <250 μm fraction through a 53 μm sieve, generated three fractions: coarse sand and particulate organic matter (cPOM; >250 μm), microaggregates within macroaggregates (mM; 53–250 μm) and macroaggregate occluded silt and clay

(Msc; <53 μm). Each of these fractions was rinsed into pre-weighed aluminum pans and oven-dried at 60 °C before weighing.

Sub-samples from each of the aggregate fractions and the bulk soils were ground and analyzed for total C and N by combustion using a Carlo Erba NA 1500 NC elemental analyzer (Fisons Instruments, Beverly, MA). Elemental concentrations were used along with bulk density measurements to calculate C and N contents a g m^{-2} basis for the top 15 cm of soil using the following formula:

$$\text{C or N in aggregate fraction} = \text{BD} \times V_{soil} \times P_{agg} \times [\text{C or N}] \quad (1)$$

where BD is the bulk density of the soil (g m^{-3}), V_{soil} is the volume of the soil in the top 15 cm (or 0.15 m^3), P_{agg} is the proportion of whole soil in the aggregate fraction of interest, and [C or N] refers to the concentration of C or N in this aggregate fraction.

2.6. Statistical analyses

Average values for the three earthworm pits in each field were used for all statistical tests (i.e., $n = 16$). The association of categorical management variables (e.g., residue management, irrigation type, etc.) with earthworm populations and various soil properties were analyzed using ANOVA. In comparisons of residue management types involving soil aggregate fractions, clay content was used as a covariate with ANCOVA, since aggregation is largely influenced by the clay content of a soil (Kemper and Koch, 1966). Relationships between earthworms, soil properties, and other continuous variables were examined using simple linear regression. Natural log transformations were applied where needed to meet the assumptions of regression and ANOVA. All analyses were conducted using JMP 7.0 (SAS Institute, 2007).

3. Results

3.1. Influence of management on earthworm populations

Earthworm populations varied dramatically across farms, such that average densities ranged from 18.5 to 451.2 individuals m^{-2}, while total earthworm fresh weight biomass ranged from 1.3 g m^{-2} to 142.3 g m^{-2}.

Of the various management and soil factors examined, residue management was most strongly related to earthworm populations across the 16 fields sampled. Fields where tomato residues were left in place had significantly higher earthworm biomass ($P = 0.024$) compared to fields under bare fallow management, with fresh weights averaging 85.4 g m^{-2} versus 18.6 g m^{-2} in the tomato mulch and bare fallow treatments, respectively (Fig. 1). Additionally, the average size (biomass) of individual earthworms was 2.9 times greater under tomato mulch management compared with bare fallow ($P = 0.020$), while sexually mature adults weighed 2.3 times more in the tomato mulch versus bare fallow treatments ($P = 0.029$). Of the five species encountered in this survey *Aporrectodea caliginosa* (Savigny) was found to be the most ubiquitous and dominant in all residue management treatments (Fig. 2), thus differences in average earthworm size do not appear to result from alterations in species abundance between management types. *Aporrectodea rosea* (Savigny) and an unidentified species from the Megascolecidae family (possibly *Microscolex dubius*; Fletcher) were found under all forms of residue management, but generally in lesser abundance (Fig. 2). Additionally, *Allolobophora chlorotica* (Savigny) was found in two fields, while *Aporrectodea longa* (Ude) was found only at a single farm, all under tomato mulch management.

Other management factors were also found to be related to earthworms (Table 3). Regression analyses revealed that earthworm biomass was positively correlated with the number of consecutive years a field had been under organic

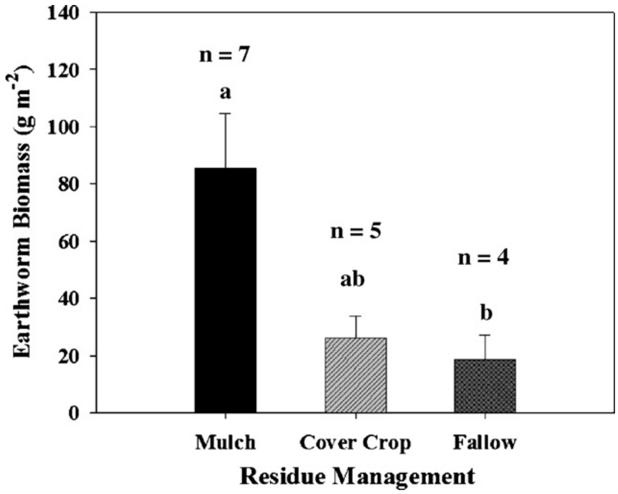

Fig. 1 – Fresh earthworm biomass under different residue management options in the western Sacramento Valley, California. Error bars represent standard error of the mean. Lowercase letters indicate statistically different means (P < 0.05) according to Tukey's HSD mean separation test on ln-transformed data.

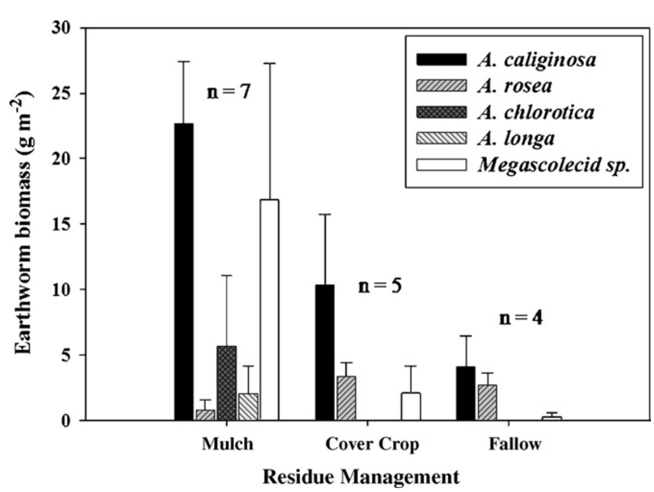

Fig. 2 – Fresh biomass of earthworm species collected under different residue management options in the western Sacramento Valley, California. Error bars represent standard error of the mean.

Table 2 – ANOVA and ANCOVA results for the association of residue management associations with earthworms and soil properties.

	Residue management		% Clay		Error d.f.
	P-value	F-ratio	P-value	F-ratio	
Earthworm indicators					
Earthworm density (worms m^{-2})	0.240	1.58	NA[a]	NA	13
Total earthworm biomass ($g\ m^{-2}$)	0.024	5.04	NA	NA	13
Individual earthworm biomass ($g\ worm^{-1}$)	0.043	4.07	NA	NA	13
Soil properties					
Total soil C ($g\ m^{-2}$)	0.049	3.83	NA	NA	13
Total soil N ($g\ m^{-2}$)	0.036	4.33	NA	NA	13
MWD[b]	0.049	3.91	0.004	13.03	12
Aggregate associated C					
Macroaggregate C ($g\ m^{-2}$)	0.023	5.26	0.015	8.07	12
cPOM[c] C ($g\ m^{-2}$)	0.001	12.70	>0.10	0.71	12
mM[d] C ($g\ m^{-2}$)	0.064	3.50	0.013	8.47	12
Msc[e] C ($g\ m^{-2}$)	0.032	4.68	0.002	15.22	12
Microaggregate C ($g\ m^{-2}$)	>0.10	0.52	0.070	3.80	12
Silt and clay C ($g\ m^{-2}$)	>0.10	0.48	>0.10	2.13	12

[a] Not applicable (clay only used as covariate in analyses involving aggregation).
[b] Mean weight diameter.
[c] Coarse particulate organic matter occluded within macroaggregates.
[d] Microaggregates within macroaggregates.
[e] Macroaggregate occluded silt and clay.

management at the time of sampling ($P = 0.013$, $R^2 = 0.36$). Tillage intensity was also associated with earthworm growth and survival, as the average biomass of earthworm individuals decreased with increasing number of tractor passes in the year prior to sampling ($P = 0.004$, $R^2 = 0.48$). The type of irrigation employed was not significantly related to earthworm populations ($P > 0.10$). Great variety in the forms of nutrient amendments applied (Table 1), along with insufficient information on the quantity and quality of these amendments prohibited analyses involving fertilizer application.

3.2. *Management effects on soil structure and SOM*

Relative to other management factors considered in this study, residue management appeared to be best associated with a number of soil properties (Table 2). For example, aggregate stability (i.e., mean weight diameter), was significantly higher for the fields under tomato mulch management compared to those under bare fallow when the clay content of the soil was used as a covariate ($P = 0.049$), such that the clay-adjusted means (least square means from ANCOVA) were 1047 μm in the tomato mulch versus 425 μm for bare fallow management. The contribution of large macroaggregates to whole soil was also higher under tomato mulch management compared to bare fallow (13.1% vs. 1.5%; respectively, $P = 0.033$), after adjusting for the percent clay in each field.

Residue management was related to both total C and N on a $g\ m^{-2}$ basis ($P = 0.049$ and $P = 0.036$; respectively), with the tomato mulch fields having 1.6 times as much C (Fig. 3) and 1.5 times as much N as the fields under bare fallow. Likewise, C and N contained within the macroaggregate fraction were significantly different across residue management types after accounting for clay content ($P = 0.023$ and $P = 0.027$; respectively), with the tomato mulch management displaying a clay-adjusted mean equal to 2.8 times more macroaggregate C and 2.6 times more N than the fields under bare fallow. A similar, yet more significant, difference is reflected in C and N stores in the cPOM fraction on a $g\ m^{-2}$ basis, with 3.7 times more C and 3.9 times more N in this fraction under tomato mulch management than with bare fallow (P values <0.005). Residue management was not significantly related to C or N found in any of the other soil fractions.

Tillage intensity was also found to be associated with soil C and N. The number of passes in the year prior to sampling was negatively correlated with both total soil C ($P = 0.043$, $R^2 = 0.32$) and N ($P = 0.039$, $R^2 = 0.33$). Tillage intensity was also inversely

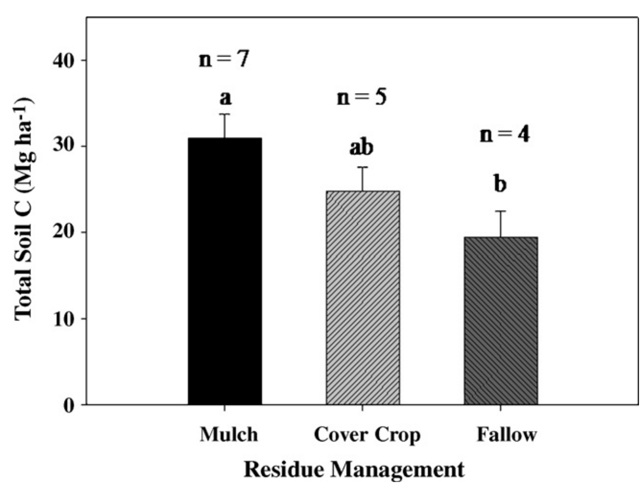

Fig. 3 – Total soil C under different residue management options in the western Sacramento Valley, California. Error bars represent standard error of the mean. Lowercase letters indicate statistically different means ($P < 0.05$) according to Tukey's HSD mean separation test.

related to C ($P = 0.029$, $R^2 = 0.42$) and N ($P = 0.039$, $R^2 = 0.41$) contained within macroaggregates on a g m^{-2} basis when using clay content as a covariate.

3.3. Relationships between earthworms and soil properties

Earthworm biomass was positively correlated with both total soil C ($P = 0.010$, $R^2 = 0.39$; Fig. 4) and N ($P = 0.010$, $R^2 = 0.039$) on a g m^{-2} basis, as well as C and N stored in microaggregates and the silt and clay fraction ($P < 0.05$, $R^2 > 0.29$). Although earthworm biomass was not related with total C or N stored in macroaggregates on a g m^{-2} basis ($P > 0.10$; Table 3), they were positively correlated with the percent of macroaggregate C found in the cPOM fraction ($P = 0.028$, $R^2 = 0.30$) and inversely related with the percent of C stored in the mM fraction ($P = 0.027$, $R^2 = 0.30$). Neither earthworm numbers nor biomass was correlated ($P > 0.10$) with soil texture, bulk density, soil moisture, aggregate stability, or the proportion of whole soil occupying any of the measured aggregate size fractions (Table 3).

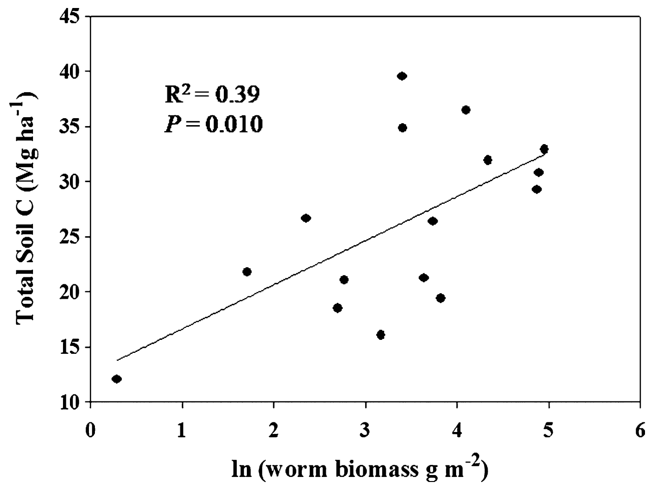

Fig. 4 – Relationship between earthworm biomass and total soil C across 16 farms in the western Sacramento Valley, California.

4. Discussion

As key regulators of SOM in many ecosystems, understanding the factors that control earthworm abundance and community structure is vital for the sustainable management of soils. Although a number of studies have examined both anthropogenic and environmental controls on earthworm populations in agricultural systems, few have sought to understand earthworm interactions with soil structure within the same framework. This study offers a unique survey of earthworms in agricultural fields of northern California and identifies possible management controls on their populations and the dynamics of aggregate-associated SOM pools.

The earthworm identified in this study consisted entirely of exotic species as is common in agricultural systems across North America (Edwards et al., 1995). Most of these same species, most notably *A. caliginosa*, are cosmopolitan species

Table 3 – Significance (P) and fit (R^2) of linear correlations involving earthworm variables vs. management and soil characteristics.

	Earthworm density (number m^{-2})		Total earthworm biomass (g m^{-2})		Individual earthworm biomass (g)	
	R^2	P-value	R^2	P-value	R^2	P-value
Management variable						
Tillage intensity (# of passes)	0.02	>0.10	0.22	0.076	0.48	0.004
Time managed organic (years)	0.15	>0.10	0.36	0.013	0.32	0.022
Soil properties						
Total soil C (g m^{-2})	0.24	0.053	0.39	0.010	0.21	0.075
Total soil N (g m^{-2})	0.20	0.080	0.39	0.010	0.25	0.049
MWD[a]	0.07	>0.10	0.01	>0.10	0.05	>0.10
% Clay	0.10	>0.10	0.13	>0.10	0.05	>0.10
% Silt	0.09	>0.10	0.00	>0.10	0.11	>0.10
% Sand	0.01	>0.10	0.06	>0.10	0.11	>0.10
Bulk density (g cm^{-3})	0.06	>0.10	0.02	>0.10	0.01	>0.10
Aggregate associated C						
Macroaggregate C (g m^{-2})	0.01	>0.10	0.03	>0.10	0.13	>0.10
cPOM[b] (% of Macroaggregate C)	0.10	>0.10	0.30	0.028	0.29	0.030
mM[c] (% of Macroaggregate C)	0.21	0.076	0.30	0.027	0.11	>0.10
Msc[d] (% of Macroaggregate C)	0.06	>0.10	0.01	>0.10	0.02	>0.10
Microaggregate C (g m^{-2})	0.35	0.016	0.37	0.012	0.06	>0.10
Silt and clay C (g m^{-2})	0.48	0.003	0.32	0.022	0.00	>0.10

[a] Mean weight diameter.
[b] Coarse particulate organic matter occluded within macroaggregates.
[c] Microaggregates within macroaggregates.
[d] Macroaggregate occluded silt and clay.

and commonly occur in temperate agroecosystems around the world (e.g., Baker et al., 1992; Whalen, 2004). Although native earthworms do exist in this region of northern California, they are thought to be competitively inferior in intensively managed soils and thus are rarely, if ever found in farmers' fields (Winsome et al., 2006).

We must note that the sampling methodology employed in this study likely excludes some deeper dwelling endogeic and anecic species and thus may not provide a complete assessment of earthworm species composition. However, the dominance of endogeic species in our samples as well as the absence of burrows below 30 cm (in all but a few pits) indicates that our findings provide at least a reasonable estimation of earthworm abundance and species composition in the areas sampled. High spatial heterogeneity commonly associated with earthworm communities (Whalen, 2004) also begs some caution in the interpretation of the results (which are based on only three samples per field). Despite these potential caveats, earthworm populations in this survey were of comparable size to those observed in other studies of temperate cropping systems (Hendrix et al., 1992; Kladivko et al., 1997; Whalen, 2004).

Of the various management factors considered, residue management appeared to be most closely related with earthworms and SOM dynamics. This finding corroborates past research demonstrating that both tillage intensity and organic matter inputs can influence earthworm populations (Fraser et al., 1996; Kladivko et al., 1997; Chan, 2001). A review by Chan (2001) suggests that cultivation does not always have adverse impacts on earthworm populations, but rather that the influence of tillage depends on the earthworm functional group as well as the tillage implement and intensities in question. Although the largely endogeic species encountered in our survey might actually be favored at low levels of tillage according to Chan (2001), we speculate that the relatively high intensity of tillage applied to these tomato systems (up to 10 passes year^{-1}; see Table 1), in addition to differences in residue handling, contributed to the clear relationship between management and earthworm populations in this study. Earthworms under tomato mulch management likely benefited from sustained soil cover, thus reducing temperature and moisture fluctuations, while decaying aboveground residues and weeds provided an uninterrupted food supply. Conversely, bare fallow management was associated with nutrient amendments that were low in C (since most of these fields were managed conventionally) and a likely rapid decay of aboveground residues following incorporation in the fall of 2004. This may have lead to a subsequent scarcity of food for much of the winter and early spring of 2005. Given that earthworm biomass was positively correlated with both total soil C and N (Fig. 4), the higher content of C and N in the fields under tomato mulch management likely served as a food source and thus contributed to greater earthworm biomass (Figs. 1 and 3) in this treatment (Lee, 1985). Larger adult biomass in the tomato mulch system as well as past research indicating a relationship between soil C and earthworm populations support this postulation (Kladivko et al., 1997; Ouellet et al., 2008). Cover cropping was associated with only marginally higher earthworm biomass compared to bare fallow management (Fig. 1); yet, this form of management offered nearly continuous soil cover and organic matter inputs. This suggests that increased tillage intensity (number of tractor passes year^{-1}) and perhaps the more recent tillage activity associated with both bare fallow and cover crop management play important roles in regulating earthworm populations as well. Earthworms in the tomato mulch treatment, for example, experienced roughly 9 months of undisturbed soil prior to sampling versus an average of 5 months for the cover crop and bare fallow treatments. The significant correlation between tillage intensity and earthworm biomass indicates that both aspects of tillage are likely to contribute to a reduction in earthworms. We must note that the association between bare fallow management and conventional agricultural practices offers the possibility that lower earthworm populations observed in the bare fallow systems may also result from the use of harmful chemical inputs (Curry, 2004), in addition to differences in tillage and residue handling.

Residue management appears to be closely associated with SOM dynamics as well (Table 2). The greatest differences were observed between the tomato mulch and bare fallow management systems, while the cover crop management (likely receiving the greatest annual C input due to both organic nutrient and cover crop biomass inputs) was intermediate in soil C and N levels (Fig. 3). This suggests that the association between residue management and SOM is driven in part by tillage intensity as well as the timing and quantity of C inputs. An influence of tillage is indicated by the inverse correlation between the number of field passes in 2004 prior to sampling and total soil C and N. Tillage generally accelerates the loss of SOM via disturbance of C contained within soil aggregates as well as redistribution of plant residues in the soil profile, thus facilitating organic matter decay (Beare et al., 1994; Paustian et al., 1997). In this study, the disruption of soil aggregates appears to play a role in altering SOM stores between residue management types. This is evident from differences in aggregate stability as well as C and N contained within macroaggregates between management treatments (Table 3). The negative correlation between tillage intensity and macroaggregate-associated C and N further supports the notion that the relative decrease in SOM stores between tomato mulch and the other two forms of residue management (Fig. 3), at least partially, results from tillage induced alterations to soil structure. The strong association between residue management and cPOM likely reflect differences in tillage as well as the timing of residue inputs and suggests that cPOM may be a sensitive indicator of disturbance associated changes to SOM (Six et al., 1998; Denef et al., 2007). Higher cPOM in the tomato mulch system suggests that this system was receiving the greatest input of partially decomposed organic matter prior to sampling.

Despite the apparent role of residue handling and associated management practices in governing earthworm populations and SOM dynamics, the observational nature of this study does not allow for determination of cause and effect. However, given the seeming lack of other factors driving earthworm and SOM dynamics, and that our findings are largely supported by past research involving manipulative experiments, we consider it likely that residue management plays a significant role in the differences observed here.

One of the principal objectives of this study was to explore linkages between earthworms and SOM dynamics. Specifically, we sought to evaluate the hypothesis that earthworms help to stabilize SOM via the incorporation of residues into macroaggregates and the mM fraction. Although we did observe a positive correlation between earthworm biomass and total soil C and N, our findings do not suggest a relationship between earthworms and soil structure as indicated in other studies (Blanchart et al., 1999; Shipitalo and Le Bayon, 2004). In fact, earthworms were not correlated with the proportion of whole soil present in any of the measured aggregate fractions (on a weight basis). The significant correlations observed between earthworms and total C and N contained within some of the fractions on a g m^{-2} basis (e.g., microaggregates, silt and clay, cPOM) may result from the relationship between earthworms and the concentration of C and N in the whole soil, since the enrichment of the bulk soil would be associated with increases in C and N contents for at least some of the aggregate fractions comprising the whole soil. Given that earthworms casting has been shown to form stable macroaggregates enriched in C (Guggenberger et al., 1996; Blanchart et al., 1999), we sought to explore linkages between earthworms and macroaggregate composition across the 16 fields samples. A positive correlation between earthworms and the proportion of macroaggregate C contained within the cPOM fraction (Table 3) agrees with previous findings of earthworm-facilitated incorporation of residues into casts (Bossuyt et al., 2004; Fonte et al., 2007). The cPOM fraction consists of relatively labile, undecomposed material that would likely serve as an ideal food source for earthworms. However, the corresponding inverse correlation between earthworm biomass and the proportion of macroaggregate C in the mM fraction does not support previous research suggesting earthworm facilitated stabilization of organic matter within the mM fraction (Guggenberger et al., 1996; Bossuyt et al., 2004; Pulleman et al., 2005). Thus, it seems that a factor other than earthworm activity (e.g., management, soil texture) may be governing aggregate and SOM dynamics across the farms sampled in this study.

The results from this study indicate that residue management (and/or associated management factors) may pose significant implications for both soil fauna and SOM dynamics. Most notably, tomato mulch management appears to encourage both earthworm abundance and community diversity. Although our findings failed to corroborate the hypothesis that earthworms enhance SOM stabilization via residue incorporation into stable aggregates, this research does identify key relationships between earthworms and SOM stores in agroecosystems. Earthworm populations appear to be closely linked with total soil C and N content, while these in turn are related to residue handing and tillage. The observational nature of this study rules out causal inferences, but the lack of correlation between earthworms and soil structure suggests that the influence of earthworms on SOM is perhaps less important than overriding environmental and management variables in row crop systems.

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