Carbon and Nitrogen Stocks and Nitrogen Mineralization in Organically Managed Soils Amended with Composted Manures

Joan Romanyà,* Noèlia Arco, Ignasi Solà-Morales, Laura Armengot, and Francesc Xavier Sans

The use of composted manures and of legumes in crop rotations may control the quality and quantity of soil organic matter and may affect nutrient retention and recycling. We studied soil organic C and N stocks and N mineralization in organically and conventionally managed dryland arable soils. We selected 13 extensive organic fields managed organically for 10 yr or more as well as adjacent fields managed conventionally. Organic farmers applied composted manures ranging from 0 to 1380 kg C ha^{-1} yr^{-1} and incorporated legumes in crop rotations. In contrast, conventional farmers applied fresh manures combined with slurries and/or mineral fertilizers ranging from 200 to 1900 kg C ha^{-1} yr^{-1} and practiced a cereal monoculture. Despite the fact that the application of organic C was similar in both farming systems, organically managed soils showed higher C and similar N content and lower bulk density than conventionally managed soils. Moreover, organic C stocks responded to the inputs of organic C in manures and to the presence of legumes only in organically managed soils. In contrast, stocks of organic N increased with the inputs of N or C in both farming systems. In organically managed soils, organic N stocks were less mineralizable than in conventional soils. However, N mineralization in organic soils was sensitive to the N fixation rates of legumes and to application rate and C/N ratio of the organic fertilizers.

In most agricultural lands, enhancing soil organic carbon (SOC) content is viewed as advantageous because it improves food security, the environment, and may mitigate the negative consequences associated with global warming (Lal, 2006). The use of manures and other organic matter amendments—while increasing SOC and nutrients—has been judged to be of little relevance in terms of mitigation of global warming as the amount of exogenous organic matter required to increase SOC stocks in one site often exceeds by far the amounts of manure produced at the site. Thus, this will have a negative impact in the marginal sites yielding this organic matter sources (Schlesinger, 2000).

Organic fertilizers have been used throughout agricultural history but, since the mid-20th century, in many cases, mineral fertilizers have replaced or largely minimized the use of manure (Wivstad et al., 2005). A reduction in the use of manures typically results in decreases in soil organic matter (SOM; Fliessbach et al., 2007; Johnston et al., 2009; Robert, 2001). However, the application of mineral fertilizers increases both crop yield and the return of plant residues to the soil and thus can also increase SOM retention. In consequence, the large-scale effects of reducing the use of manures in soil organic matter stocks is not yet well established. Large-scale, long-term studies on SOC changes in agricultural lands have quantified the changes during one, two, or three decades (Bellamy et al., 2005; Pan et al., 2010). These studies show consistent increases or decreases in SOC depending on the area of study. Soil organic carbon increases can be attributed to increases in rainfall while decreases can be partly due to rising temperatures and/or declining rainfall, all as a result of climate change or expansions in arable land to match the current food demand (Johnston et al., 2009). Continued decreases in soil organic matter in wide cropping areas have also been reported in tropical areas (Oades et al., 1989) and elsewhere (Luo et al., 2010). Thus, it seems likely that arable soils have been losing SOC during a large part of the 20th century due to land-use intensification and/or to temperature increases in wide areas of the world. Indeed, arable lands in dry areas often show very low levels of SOC, even falling below 1% (Romanyà and Rovira, 2011). These very low levels

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*Corresponding author (jromanya@ub.edu).
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5585 Guilford Rd., Madison, WI 53711 USA

J. Romanyà, N. Arco, and I. Solà-Morales, Departament de Productes Naturals, Biologia Vegetal i Edafologia, Universitat de Barcelona, Av. Joan XXIII s/n, Barcelona, E-08028, Spain; L. Armengot and F.X. Sans, Departament de Biologia Vegetal, Universitat de Barcelona, Av. Diagonal 645, Barcelona, E-08028, Spain.
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Abbreviations: SOC, soil organic carbon; SOM, soil organic matter.

may indicate land degradation involving significant reductions in crop yields (Loveland and Webb, 2003). Under these conditions, it is very likely that SOC increases will be followed by significant yield increases (Lal, 2006) and that all these soils depleted in SOC may have high stabilization capacity for soil C. The need to enhance the residence time of the SOC pool necessitates identification of practices that enhance recalcitrance against microbial decomposition (Lal, 2009).

Soil organic carbon stocks result from a steady state between climate, soil characteristics (mainly texture), and organic matter inputs (Johnston et al., 2009). Although it has been shown that decreasing plowing intensity increases SOC levels (Lopez-Fando and Pardo, 2011), inputs of organic carbon are also believed to be a very relevant aspect affecting SOC stocks (Watson et al., 2002). Inputs of SOC in agricultural soils primarily depend on crop productivity, but also on crop residue management and use of organic amendments (Johnston et al., 2009). In most industrialized countries, organic farming systems have been slowly and continuously gaining ground in recent decades (Willer et al., 2008). These systems exclude the use of synthetic fertilizers and use organic fertilizers as the main strategy for soil fertilization. However, in many areas, the availability of manures from organic stock raising farms is often low (Stockdale et al., 2001). Thus, organic farming systems in these areas commonly use exogenous composted manures from neighboring conventional stock-raising farms. During composting, organic residues undergo structural and chemical changes that slow down their decomposition rates by increasing their stability to microbial degradation (Dresboll and Magid, 2006). While composting manures in tropical countries can produce losses of C of up to 69% and between 62 and 76% for total N (Tittonell et al., 2010), available local information for the Mediterranean area on C losses from the composting of manures ranges from 20 to 34% and N losses are negligible as leachates are commonly used for irrigating compost heaps (Soliva, 2001). The use of composted materials has been shown to raise SOC stocks higher than fresh manures (Fliessbach et al., 2007; Raupp, 2001). Nevertheless, this is not always the case (Celik et al., 2010; Delschen, 1999; Fliessbach et al., 2007; Raupp, 2001) and some authors have pointed out that the stabilization of manure by composting seems to play a secondary role, if any, on increasing C stocks (Leifeld et al., 2009). On the other hand, N mineralization in soils amended with composted manures is much lower than in soils amended with fresh manures (Ribeiro et al., 2010). Low N mineralization in soils receiving compost may reduce productivity and consequently crop residues inputs. Moreover, the effects of fertilizing with mineral N on SOC stocks remain controversial (Powlson et al., 2010; Russell et al., 2009). It has been shown that an abundance of mineral N in soil may reduce C pools in the microbial biomass (Heitkamp et al., 2009; Mulvaney et al., 2009; Powlson et al., 2010) and in some cases it may also lower the metabolic quotient (qCO_2; Rudrappa et al., 2006), thus favoring soil C retention and the process of humification. Even so, in some field studies on annual crops, it has been shown that the additions of mineral N can stimulate soil organic matter decomposition and counteract the positive effects of N fertilization on the SOC stocks (Russell et al., 2009).

Legume crops are another N source. These crops, through root deposition, have been found to incorporate to the soil significant amounts of N (Gylfadottir et al., 2007; Rasmussen et al., 2007). These sources of N are mainly soluble or easily decomposable and have a fast turnover (de Graaff et al., 2007). This N can be incorporated into different pools such as microbial biomass or SOM (Mayer et al., 2003).

We hypothesize that land application of composted sources of C and N will facilitate the long-term build-up of SOC and N stocks and that the introduction of legumes may enhance N mineralization. This paper presents data on the SOC and N stocks, N mineralization capacity, and crop productivity of 13 organic farms using composted manures and incorporating legumes in crop rotation. This paper compares them to 13 conventional adjacent sites with cereal monoculture using slurries combined with fresh manures and mineral fertilizers on cereal monocultures. We aim to determine the long-term fate of added organic C and N stocks after the use of composted manures and legumes as opposed to the use of the more labile slurries and fresh manures combined with mineral fertilizers. In analyzing the sensitivity to fertilization practices, we also introduce the N inputs derived from legumes in the organic farms and consider climatic data, soil texture, and crop productivity.

Material and Methods

The Study Area and Experimental Design

The study was performed on a set of 26 agricultural fields located in central Catalonia (northeastern Spain; specifically from 42°03′21″ N, 1°46′16″ E to 41°23′41″ N, 1°05′54″ E). The climate of the area is warm temperate with dry summers (Table 1), soils are Typic Xerochrepts with carbonates (pH ranges from 7.4 to 8.8) and heavy textured (Table 1). Climatic data were obtained from the Digital Climatic Atlas of Spain (http://opengis.uab.es/wms/iberia/en_index.htm [accessed 24 Apr. 2012]; Ninyerola et al., 2000).

To study long-term changes in soils, we selected 13 independent fields with cereals that had been farmed organically for at least 10 yr. Within a few hundred meters from each organically managed field, we selected a conventionally managed field (13 additional fields altogether). In the sampling year, all fields were cultivated with wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.). Each selected field belonged to a different farmer, so the selected fields represented a wide range of farming styles in terms of fertilization rates covering organic and conventional farming practices. None of the included farms was managed using zero-tillage or minimum tillage. To characterize the fertilization practices of each studied field for the past 10 yr, we interviewed the 26 selected farmers. Organic farmers maintained records on their rotation histories as requested by the local authorities. The selected organic farmers used farmyard manure of different origins that were composted for at least 6 mo before their field application. Based on the information gathered in the interviews and using local tables of fresh and composted manures, mean annual inputs of C and N from fertilization practices were calculated for each field. Crop residues were not considered (Table 2). Nitrogen inputs from symbiotic N fixation were calculated from the number of legume crops in each crop rotation, legume production, and the percentage of N derived from the atmosphere obtained from the literature and from field measurements available in the area of study (Table 3). Legume crops replaced the cereal crops in all cases. Only *Vicia ervilia* (L.) Willd. crops and *Onobrychis viciifolia* Scop. were extended off season.

Soil Sampling and Analysis

In each field four sampling areas were randomly selected. From each one of these areas, three soil samples were collected at 0 to 10, 10 to 20, and 20 to 30 cm of depth using a prismatic volumetric auger (5- by 5-cm sections). A bulked soil sample per depth and sampling area was obtained. Georeferences for each sampling area were recorded by a GPS receiver (Model Sportrack, Magellan). All soils were sampled in late autumn to early winter after sowing and before stem elongation of the cereal. Bulk density was measured in the field by using the abovementioned volumetric augers. Bulk density was calculated by subtracting the stone and gravel volume in each sample, assuming a stone density of 2.65 g cm^{-3}.

Soil samples were air-dried and sieved (2 mm) before analysis. The soil pH was determined in water (soil water ratio 1:2.5). Mineral nitrogen was extracted with 2 M (1:5 soil:extractant ratio). Nitrate was determined by ultraviolet spectrometry at 220 and 275 nm (Yang et al., 1998). Ammonium N was determined in the filtrates by the phenate method and quantified at 640 nm using a CECIL (CE7200; Cecil Instruments) spectrophotometer (Emteryd, 1989). To determine potentially mineralizable N, all 2-mm-sieved soils were anaerobically incubated for 7 d after submerging them in deionized water. Incubated and nonincubated soil samples were shaken for 1 h and filtered. Potentially mineralizable N was determined as difference between ammonium N after and before soil incubation (Bundy and Meisinger, 1994). Soil texture was determined by sieving

Table 1. Mean annual temperature (T), rainfall, potential evapotranspiration (PET), and fine silt and clay contents of the studied sites.

Location	Organic fields					Conventional fields				
	T	Rainfall	PET	Fine silt	Clay	T	Rainfall	PET	Fine silt	Clay
	°C	— mm —		— mg g^{-1} —		°C	— mm —		— mg g^{-1} —	
Bal	13.5	635.7	535.8	335	239	13.3	649.8	515.0	261	236
Cal	12.6	688.1	506.7	184	138	13.0	676.3	508.7	246	171
Car	12.2	649.9	475.0	304	205	12.2	648.8	474.6	356	220
Cas	12.4	745.7	558.0	219	168	12.3	732.4	552.8	176	193
Ciu	12.8	503.0	405.6	336	267	12.9	495.9	402.7	325	244
Fra	14.0	535.3	424.5	257	286	13.9	521.6	423.1	392	223
Ma1	13.8	572.8	453.6	166	148	13.7	578.2	454.9	135	128
Ma2	14.1	551.1	448.2	150	187	13.9	574.6	454.9	145	149
Mas	12.9	520.2	423.9	231	247	12.9	519.4	423.6	330	259
Moi	12.0	698.7	499.8	325	197	11.9	720.4	512.2	262	168
Pil	12.1	576.4	440.4	381	274	12.6	565.7	441.7	357	261
Rin	11.6	670.0	482.5	322	187	11.6	671.0	483.1	295	171
Vic	12.8	713.0	535.9	249	229	12.8	711.1	536.4	300	190

Table 2. Fertilization practices in each of the studied fields. Figures are the mean of the inputs of the last 10 yr.

Location	Organic fields				Conventional fields				
	Amendment	Total inputs			Amendment	Total inputs		N in organic sources	
		C	N	C/N		C	N	N	C/N
		– kg ha^{-1} yr^{-1} –				— kg ha^{-1} yr^{-1} —			
Bal	Composted poultry + dairy manures	191	17	11.4	Swine slurry + mineral	56	74	12	4.6
Cal	Composted dairy manure	849	74	11.5	Swine slurry + dairy manure + mineral	437	74	52	8.4
Car	Composted dairy manure + some dairy slurry	1053	97	10.8	Swine slurry	978	214	214	4.6
Cas	No exogenous additions	0	0	–	Swine slurry + poultry and horse manures + mineral	1899	200	194	9.8
Ciu	Composted poultry manure	83	7	11.5	Swine slurry + mineral	646	146	134	4.8
Fra	No exogenous additions	0	0	–	Mineral	0	60	–	–
Ma1	Composted poultry + dairy manures	356	31	11.4	Dairy manure + mineral	167	57	12	13.9
Ma2	Composted dairy manure	1034	90	11.5	Poultry manure + swine slurry	1101	195	195	5.6
Mas	Composted dairy manure	579	51	11.5	Swine slurry + mineral	210	143	46	4.6
Moi	Composted dairy manure	236	21	11.5	Swine slurry	548	120	120	4.6
Pil	Composted dairy + rabbit manures	986	76	12.9	Swine slurry + mineral	754	191	165	4.6
Rin	Composted sheep manure	247	23	10.6	Swine slurry + dairy manure + mineral	597	122	122	4.9
Vic	Composted dairy manure + commercial organic fertilizers	1378	135	10.2	Swine slurry + dairy manure + mineral	1239	225	181	6.8
Mean		538	48	11.3		666	140*	111*	6.4*

* Significant difference between organic and conventional fields ($p < 0.05$).

and sedimentation using the Robinson pipette method (Gee and Bauder, 1986). A subsample of the fine earth from each sample was finely ground in an agate mortar to analyze total organic C and total N (Mebius, 1960). Total organic C was determined by dichromate oxidation. Total N was measured in an elemental analyzer (Carlo Erba NA-1500).

Crop Production

Cereal crop and weed aboveground biomass were determined at the late grain ripening stage (late spring, early summer). All sampling areas were relocated by the GPS, and plant sampling was performed in the same areas where soil samples had been taken. At each sampling spot the total aboveground biomass of four 0.25- by 0.25-m plots was clipped at ground level. Cereal crop biomass was separated from weed biomass for calculating total aboveground crop production and total plant production (aboveground crop + weed production). Biomass was weighed after drying at 60°C for 48 h.

Statistical Analyses

Differences between farming systems (organic and conventional) and their interaction with soil depth were tested by a randomized complete block design with subsampling ANOVA in which the farming system and soil depth interacted with the block effect (locality). Each locality consisted of a pair of conventional and organic fields and was taken as a replicate of the farming systems. The interaction between farming system, soil depth, and locality was used as the error of the model to calculate the significance.

The effects of exogenous C and N inputs on soil C and N pools in organic and conventional fields were tested using a one-way analysis of covariance, which included the interaction between the factor and the covariable. Exogenous inputs were used as covariables. Pearson correlations were performed between C and N pools and exogenous inputs, climatic, and soil data. Multiple regressions were performed using the stepwise procedure at a statistical significance of 0.05. To include the nonlinear relationships that may occur between variables in the regression models, all variables were transformed using the natural logarithm [$\ln(xi + 1)$]. To achieve normality and homogeneity of variance, proportions were transformed by the arcsine square root before statistical analyses. All statistical analyses were performed with PASW Statistics 17 (IBM SPSS Statistics).

Results

Fertilization Practices

There was a wide range of fertilization practices in both organic and conventional fields (Table 2). In the organic fields C inputs ranged from 0 to 1400 kg ha^{-1} yr^{-1}, while in conventional fields they ranged from 0 to 1900 kg ha^{-1} yr^{-1}. This wide range of application rates resulted in no significant differences in C inputs between organic and conventional fields (Table 2). The range of application of N in the conventional fields ranged between 60 and 225 kg ha^{-1} yr^{-1}, while in organically managed fields it ranged between 0 and 135 kg ha^{-1} yr^{-1}, a significantly lower range than in conventional fields. However, the organic farms had additional inputs of N derived from symbiotic fixation that ranged from 0 to 22 kg N ha^{-1} yr^{-1}. Although the symbiotic N was less than the manure N inputs, it represented the main N input at four sites (Table 3).

Soil Organic Carbon and Nitrogen Concentrations and Stocks

Soil concentrations of organic C and N were higher in organically managed soils (Table 4). Carbon-to-nitrogen ratios were slightly greater in organically managed fields compared with conventionally managed fields. Moreover, organically managed fields showed a slight reduction (3%) in bulk density,

Table 3. Time basis percentage of each legume species and of total legumes in crop rotation of the organic fields, legume aboveground annual production, and estimated N inputs by N fixation. Nitrogen fixation is the mean of the last 10 yr.

Location	Legume species in crop rotation	Legumes	Production	Legumes	Estimated N fixation
		%	kg ha^{-1} yr^{-1}	%	kg N ha^{-1} yr^{-1}
Bal	*Vicia ervilia* (L.) Willd.	21	1500	36	6.2
	Cicer arietinum L.	14	300		
Cal	*Vicia sativa* L.	8	1500	25	14.4
	Pisum sativum L.	17	2100		
Car	*Vicia sativa*	17	1500	42	24.6
	Onobrychis viciifolia Scop.	25	5000		
Cas	*Cicer arietinum*	20	2000	20	5.9
Ciu	*Vicia sativa*	13	3250	13	7.1
Fra	*Pisum sativum*	16.5	1500	33	16.2
	Lens culinaris Medik.	16.5	1500		
Ma1	*Vicia sativa*	10	450	10	3.1
Ma2	*Vicia sativa*	5	1850	20	6.5
	Vicia ervilia	15	1850		
Mas	*Vicia sativa*	17	1500	17	4.4
Moi	*Vicia sativa*	19	1100	61	22.0
	Onobrychis viciifolia		2650		
Pil	*Cicer arietinum*	17	400	17	1.0
Rin	*Cicer arietinum*	33	300	33	1.5
Vic	–	0	0	0	0.0
Mean				25	8.7

which reduced the differences in C and N stocks to 10 and 5.5%, respectively, relative to conventionally managed soil. Increases in organic C and N stocks in the organically managed soils relative to conventionally managed soils represented 0.53 kg m^{-2} for organic C and 32.6 g m^{-2} for N. Cereal production and crop + weed production were 29 and 23% lower, respectively, in organically managed fields.

Analyses of the Soil Organic Carbon and Nitrogen Stocks

Soil organic carbon stocks significantly increased with exogenous C inputs only in organic fields (Fig. 1). Similarly, SOC stocks increased with increasing N inputs only in organically managed fields. Stepwise multiple regression analyses showed positive relationships between SOC stocks and the soil mineral N and the percentage of legumes in crop rotation (Table 5). Potentially mineralizable N and actual evapotranspiration also showed positive relationships with SOC stocks. In conventional fields neither the total C or N inputs bore any relation to SOC stocks. No multiple regression functions were found for the SOC stocks in conventional fields. Moreover, the N inputs in slurry and fresh manures (excluding N in mineral fertilizers) did not show any relation to the SOC stocks.

In contrast, N stocks were highly sensitive to the exogenous N inputs for all treatments irrespective of the input source. However, the slopes of the curves were steeper for the organically managed fields (Fig. 1), even when conventional fields were plotted as a function of the N inputs contained in slurry and fresh manures (data not shown). Multiple regression analyses showed the soil mineral N and again the exogenous N inputs as important variables for the N stocks irrespective of the management practices. Additionally, only for the organically managed soils plant production, percentage of legumes, the potentially mineralizable N, and clay content were also significant variables (Table 5). Soil organic carbon stocks in conventional fields showed strong relationships with climatic data, while in organic fields these relationships were weaker (Table 6).

Table 4. Aboveground production and soil properties in the three studied soil layers. Significance levels of model effects are shown for farming system and soil depth.

		Organic	Conventional
	Crop production (Mg ha^{-1} yr^{-1})	7.8 ± 1.20	11.0 ± 0.9
	Crop + weed production (Mg ha^{-1} yr^{-1})	9.2 ± 1.10	11.9 ± 0.9
Soil depth (cm)			
0–10	C (%)	1.47 ± 0.70	1.37 ± 0.5
	N (mg g^{-1})	1.60 ± 0.05	1.50 ± 0.05
	C/N	9.18 ± 0.32	9.03 ± 0.28
	C (kg m^{-2})	1.92 ± 0.09	1.85 ± 0.08
	N (g m^{-2})	207.1 ± 7.10	197.9 ± 6.90
	BD† (g cm^{-3})	1.35 ± 0.02	1.40 ± 0.02
10–20	C (%)	1.31 ± 0.07	1.14 ± 0.05
	N (mg g^{-1})	1.40 ± 0.05	1.30 ± 0.03
	C/N	9.14 ± 0.34	8.79 ± 0.34
	C (kg m^{-2})	2.03 ± 0.12	1.87 ± 0.09
	N (g m^{-2})	218.3 ± 8.0	209.3 ± 7.2
	BD (g cm^{-3})	1.64 ± 0.03	1.69 ± 0.02
20–30	C (%)	1.12 ± 0.06	0.89 ± 0.04
	N (mg g^{-1})	1.17 ± 0.05	1.05 ± 0.03
	C/N	9.42 ± 0.34	9.17 ± 0.34
	C (kg m^{-2})	1.91 ± 0.12	1.61 ± 0.09
	N (g m^{-2})	199.8 ± 10.7	185.4 ± 7.2
	BD (g cm^{-3})	1.81 ± 0.02	1.86 ± 0.02
Total (0–30 cm)	C (kg m^{-2})	5.86 ± 0.79	5.33 ± 0.74
	N (g m^{-2})	625.2 ± 21.50	592.6 ± 17.1
Significance level			
	Farming system (FS)	**Depth**	**FS × Depth**
Crop production	0.000	–	–
Crop + weed production	0.000	–	–
C (%)	0.000	0.000	NS
N (mg g^{-1})	0.003	0.000	NS
C/N	0.031	NS	NS
C (kg m^{-2})	0.048	0.007	NS
N (g m^{-2})	NS	0.003	NS
BD (g cm^{-3})	0.009	0.000	NS
C (kg m^{-2})	NS	–	–
N (g m^{-2})	NS	–	–

† Bulk density.

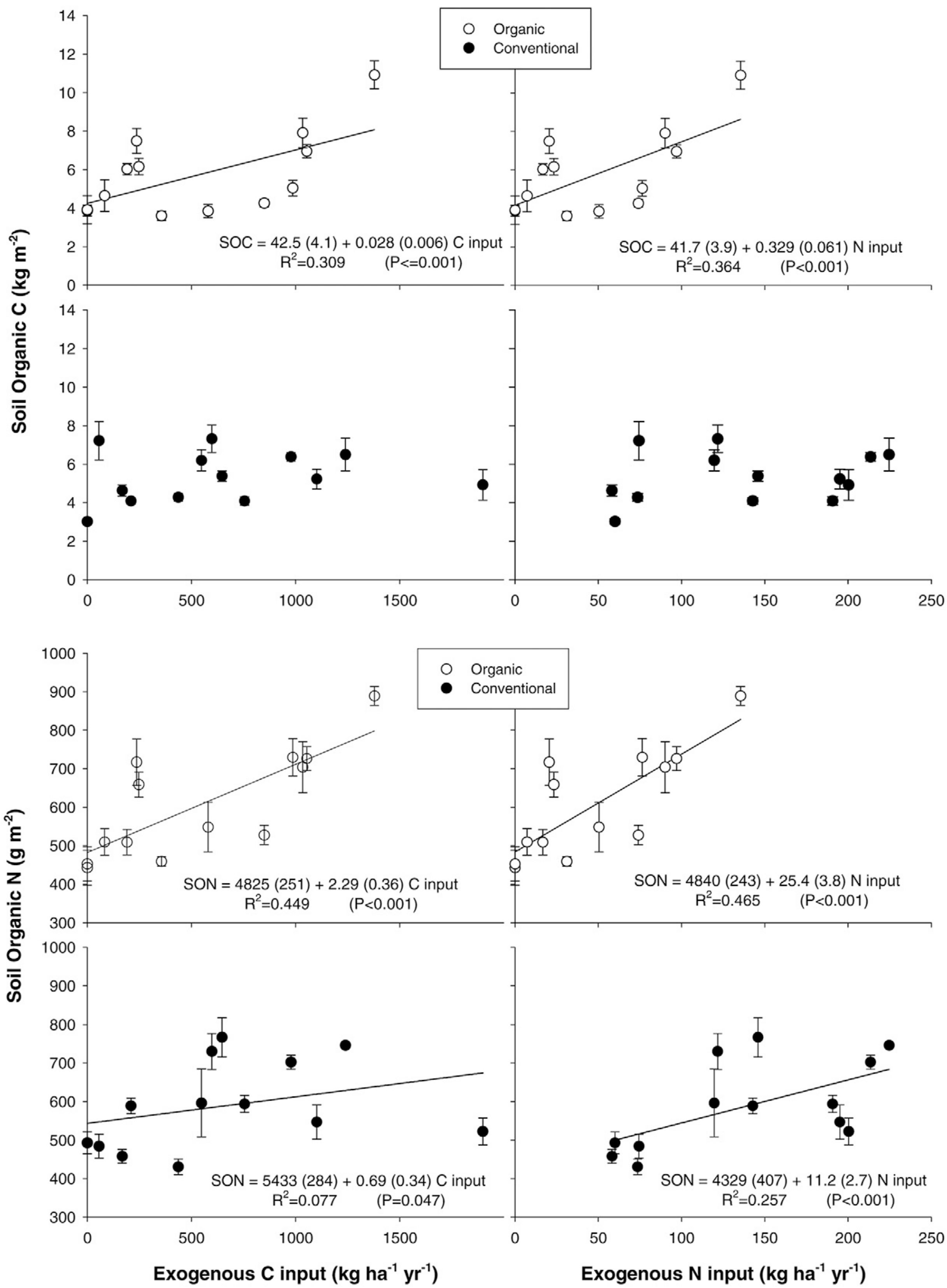

Fig. 1. Organic C and N stocks in the top 30 cm of cereal crop soils as a function of exogenous input of C and N in soils organically managed with composted inputs or conventionally managed with fresh manure, slurry, and mineral fertilizer for at least the last 10 yr. Significant regression equations are shown. The standard error of each parameter is shown in parentheses. SOC, soil organic carbon; SON, soil organic nitrogen.

Table 5. Stepwise multiple regressions models between the stocks of C and N and of potentially mineralizable N (PMN) of the soils of the organically and conventionally managed fields and the variables describing soils, management, and climate. Standard error of each coefficient is shown in parentheses.

Farming model	Variable	Multiple regression equation†	R^2
Organic	C (kg m^{-2})	26.1 (5.1) + 0.23 (0.03) Nmin + 35.7 (12.6) % Legum.	0.680
	C (kg m^{-2})	–69.9 (4.0) + 0.20 (0.03) Nmin + 0.21 (0.05) AET + 0.07 (0.3) PMN	0.773
Organic	N (kg m^{-2})	4231.7 (353.9) + 10.0 (2.0) Nmin + 0.08 (0.03) Plant production	0.625
	N (kg m^{-2})	2458.0 (710.4) + 9.1 (2.0) Nmin + 2590.7 (848.0) % Legum. + 16.7 (4.5) N input + 26.4 (12.8) Part < 20 µm	0.701
	ln N	9.9 (0.4) + 0.0017 (0.0004) Nmin – 0.12 (0.03) T °C + 0.001 (0.0004) PMN + 0.0001(0.00007) C input	0.734
Conventional	N (kg m^{-2})	3494.2 (406.4) + 6.5 (1.5) Nmin + 9.3 (2.3) N input	0.451
	ln N	8.2(1.0) + 0.0013 (0.0002) Nmin + 0.69 (0.02) ln (N input)	0.574
Organic	PMN (g m^{-2})	–367.6 (140.8) + 52.9 (12.8) C/N input + 3.1 (1.0) N leg. input – 2.3 (0.8) Part < 20µm	0.424
	ln (PMN)	–1.2 (1.1) + 0.6 (0.1) C/N input – 0.03 (0.006) Part < 20µm + 2.0 (0.4) % Legum.	0.630

† Nmin, soil mineral nitrogen; PMN, potentially mineralizable N; % Legum., time percentage of legumes in crop rotation; Plant production, aboveground crop + weed production; N input, the inputs of N in manures; C input, input of C in manures; N leg. input, the N inputs from legume crops; Part < 20 µm, percentage of fine particles; AET, actual evapotranspiration; T °C, mean annual temperature.

Table 6. Pearson correlation coefficients depicting the dependence of the stocks of organic C and N on the climatic data, crop productivity and soil clay content. The significance of the correlation (in italics) and the number of observations are also shown.

Climate and plant production	C stocks		N stocks	
	Organic	Conventional	Organic	Conventional
	kg ha^{-1}			
Temperature (°C)	NS	–0.428 (*0.002*) 52	–0.341 (*0.013*) 52	–0.481 (*0.000*) 52
Rainfall (mm)	0.350 (*0.011*) 52	0.454 (*0.000*) 52	NS	NS
Potential evapotranspiration (mm)	NS	–0.418 (*0.001*) 52	–0.333 (*0.016*) 52	–0.474 (*0.000*) 52
Water deficit (mm)	–0.314 (*0.024*) 52	–0.475 (*0.000*) 52	NS	NS
Crop + weed production (kg ha^{-1} yr^{-1})	0.399 (*0.005*) 48	NS	0.566 (*0.000*) 47	NS
Clay (%)	NS	NS	NS	NS

Potentially Mineralizable Nitrogen

Potentially mineralizable N increased with soil organic C and N in all fields. The amount of N mineralized per unit of organic C or per unit of organic N was lower in organically than in conventionally managed soils (Fig. 2). Potentially mineralizable N was sensitive to C and N inputs only in organically managed soils (Fig. 3). Potentially mineralizable N showed highly significant multiple regressions with N derived from symbiotic fixation, the percentage of legumes in crop rotation, the C/N ratio of manures, and the percentage of particles finer than 20 µm (Table 5).

Discussion

Soil Organic Carbon Stocks

In the soils studied, SOC stocks for the top 30 cm of soil ranged from 3.9 to 10.9 kg m^{-2} in organic soils and from 3.0 to 7.2 kg m^{-2} in conventional soils. These values are representative of the wet Mediterranean area of Spain (Romanyà and Rovira, 2011). They are more than three times higher than the values reported for the Mediterranean soils of central Spain (Hernanz et al., 2009) and are, in most cases, higher than the mean values of the arable lands of France (4.3 kg m^{-2}) and Spain (5.1 kg m^{-2}; Robert, 2002; Rodriguez-Murillo, 2001). In spite of the wide ranges observed in the two farming systems, organic soils showed higher SOC stocks than conventional soils as a result of the sharp differences in SOC observed in localities in which the organic fields received large amounts of organic C (>1 kg C m^{-2} yr^{-1}) in the form of composted manures.

Fertilization Practices and Soil Organic Carbon Stocks

Stocks of SOC in organically managed soils were highly sensitive to the fertilization practices of the last 10 yr. In these soils the stocks of C were also sensitive to the use of legumes and to the available forms of N. In contrast, in conventionally managed soils receiving slurries and fresh manures combined with mineral fertilizers, SOC stocks were largely independent of both the inputs of exogenous organic C and N and of the available forms of N. In other studies, the use of labile sources of C, such as slurries even at high rates, has not resulted in an increase in C stocks because the labile C quickly mineralizes and stimulates (priming effect) the decomposition of SOC (Angers et al., 2010). In our study, the organic farming practices such as the use of composted manures and the inclusion of legumes into crop rotation has produced a mean increase in SOC stocks of about 0.53 kg m^{-2} that would be mainly applicable to soils

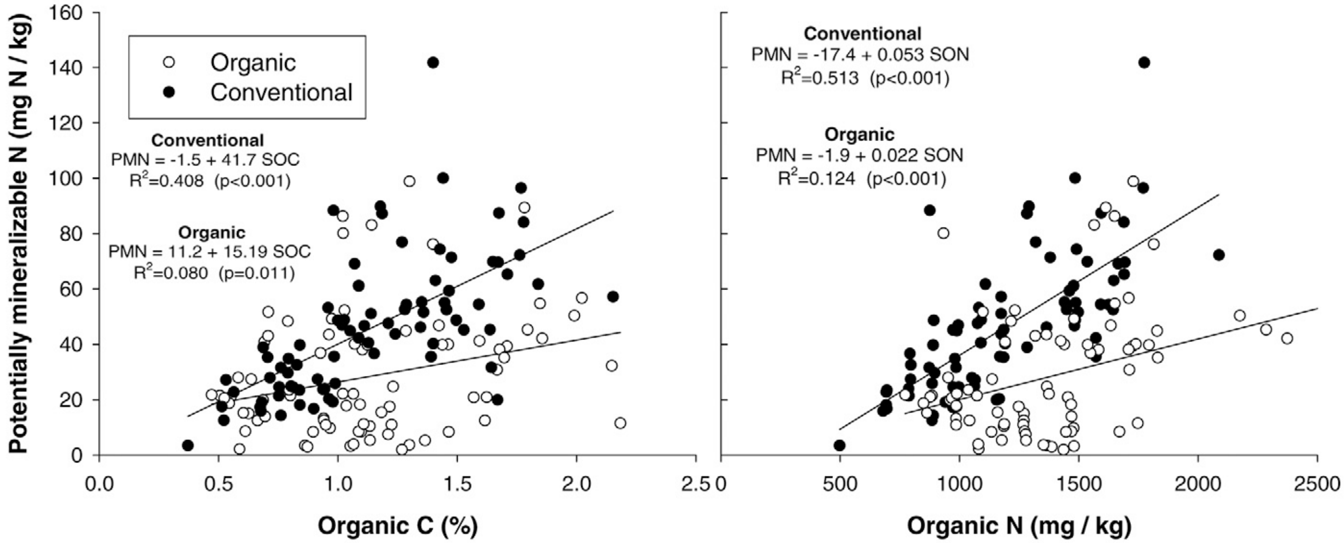

Fig. 2. Potentially mineralizable N (PMN) as a function of soil organic carbon and soil organic nitrogen content in soils organically managed or conventionally managed with composted inputs or conventionally managed with fresh manure, slurry, and mineral fertilizer for at least the last 10 yr. Significant regression equations are shown. The standard error of each is shown in parentheses.

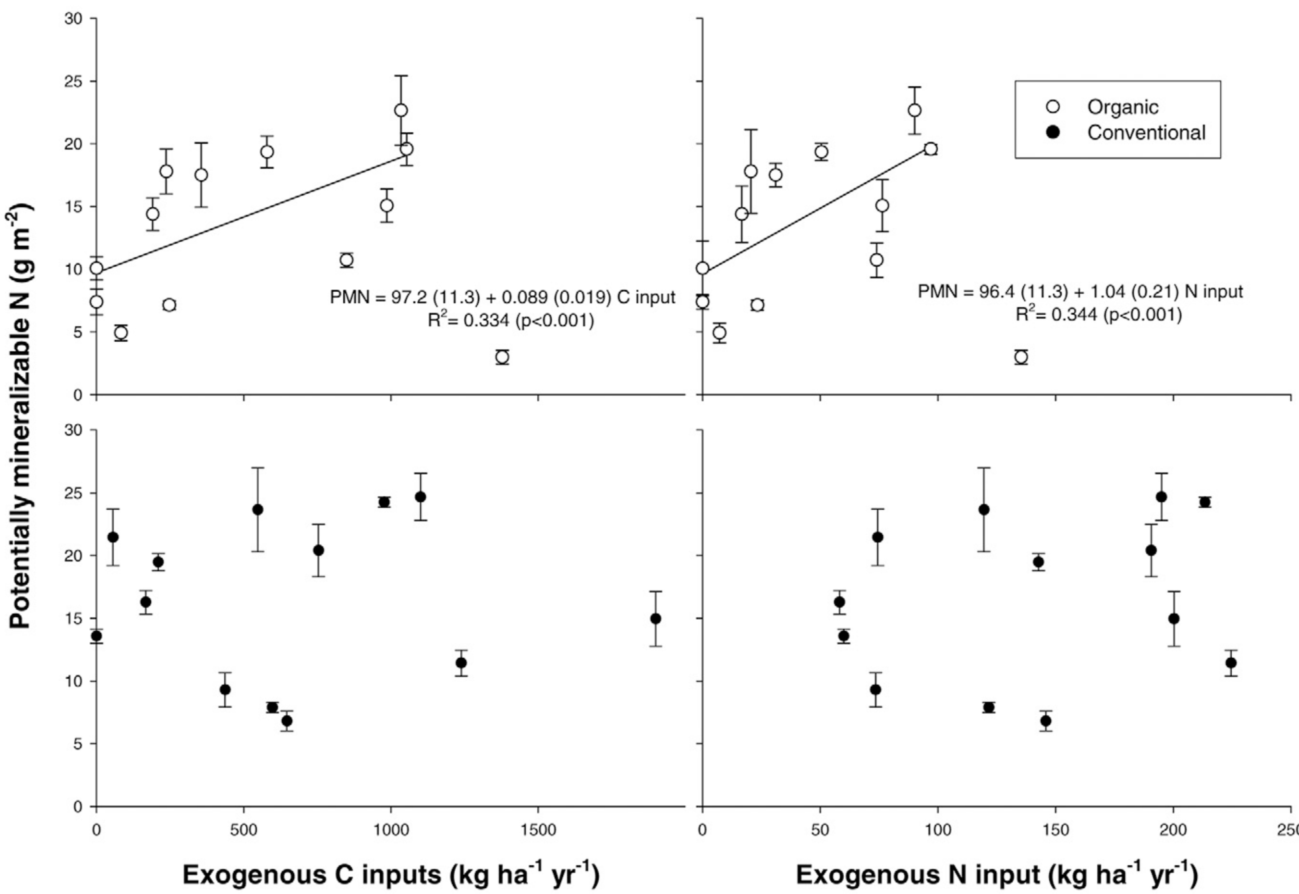

Fig. 3. Potentially mineralizable N (PMN) in the top 30 cm of cereal crop soils vs. exogenous C and N inputs in soils organically managed or conventionally managed for at least the last 10 yr. Significant regression equations are shown. The standard error of each parameter is shown in parentheses. One outlier in the organically managed soils was excluded from the analysis: its rotation did not include a legume.

receiving 1 to 1.5 kg C m^{-2} yr^{-1} and with legumes representing one-third or more of the crops in the rotation. Positive responses of SOC stocks to the addition of manures or to the inclusion of legumes in the cropping systems have been reported in the literature (Beedy et al., 2010; Freibauer et al., 2004). Carbon accrual in soil can be affected by the stability of the SOC pools and the supply of nutrients such as N (Beedy et al., 2010). The greater stability of the SOC pools that has been found in some organically managed soils (Fliessbach and Mäder, 2000) may explain the high organic C retention capacity of these soils (Fliessbach et al., 2007; Raupp, 2001). These differences may be attributed to the fertilization strategy in which composted or partly composted materials have been used without any addition of mineral fertilizers. On the other hand, the use of legumes increases active SOC pools (Wander et al., 1994), although this practice has only produced very small increases on SOC stocks (Beedy et al., 2010; Wander et al., 1994). Indeed, our data on organically managed soils showed a strong relationship with fertilization practices and with the most available forms of N while the effects of legumes only showed a secondary role.

Others have pointed out that organic matter that has already undergone some level of decomposition is more efficient in building up SOM than fresh organic matter (Bhogal et al., 2009; Dick and Gregorich, 2004). As has been widely stated, the additions of fresh organic matter can prime the decomposition of soil organic matter pools that otherwise would be stable (Brookes et al., 2008; Fangueiro et al., 2007). The use of stable sources of soil organic matter may reduce or avoid this priming effect and prevent the losses of the native pools of soil organic matter with manure amendment.

Soil Organic Carbon Concentration and Bulk Density

The differences in SOC concentration between organic and conventional farming systems were large. The increases in SOC observed in the organically managed soils corresponded in part to a significant reduction in soil bulk density compared to conventionally managed soils that was consistent across the three studied layers down to 30 cm of depth. The reduction in bulk density lowered the differences in soil organic C stocks between the two farming systems. This suggests that changes in soil bulk density resulting from increases in soil organic C content must be considered when accounting for C stocks in arable lands. Decreases in top soil bulk density in 0- to 15-cm soils have also been found in temperate arable soils after receiving exogenous organic C (Bhogal et al., 2009). In these latter soils, it has also been shown that the incorporation of crop residues did not increase soil bulk density, suggesting that changes in soil bulk density may depend on both the quality and/or the incorporation rates of the sources of organic matter. From our data we cannot determine whether the increases in bulk density should be attributed to the quality of the organic sources alone or also to the effects of legumes. However, other authors found larger decreases in bulk density or larger increases in porosity in soils receiving compost than in soils receiving fresh manures (Barzegar et al., 2002; Celik et al., 2010). It has been suggested that the addition of well-decomposed composted materials may have a stronger impact on soil aggregation than the addition of easily decomposable materials (Haynes and Naidu, 1998). The physical presence in the soil aggregates of the remaining debris of manures can decrease soil density and increase soil porosity and water retention (Bhogal et al., 2009). Thus, the application of stabilized sources of organic carbon may be beneficial especially in soils with low organic carbon reserve and with poor structure.

Nitrogen Stocks and Mineralization and Plant Productivity

Nitrogen stocks increased with N inputs and with the pools of mineral N in both management scenarios. Other studies have also shown increases in soil N in response to the use of manures (Mallory and Griffin, 2007) or labile sources of N such as slurries (Angers et al., 2010). This suggests that soil N retention relates to the quantity of added N rather than to their quality. However, the steeper slope of the curve suggests that N applied with stabilized materials is more likely to be retained in soils than N applied with fresh manures, slurries, and mineral fertilizers. As suggested by Becker and Ladha (1997), the high stability of N in stabilized manures would increase the N retention capacity of soils.

Soils with increased N stocks resulting from manure application (Bhogal et al., 2009; Mallory and Griffin, 2007; Nett et al., 2010) or mineral fertilizer (Heitkamp et al., 2009) often show high N mineralization rates. In our study the highest mineralization rates were observed in the conventional soils fertilized with sources rich in mineral N. However, these soils did not show increases in N mineralization per unit of added N as it occurred in soils amended with stabilized manures. This may be due to the inhibition effect of the mineral N added in mineral fertilizer, slurries, and fresh manures.

Organically managed soils, in spite of receiving much lower inputs of N, showed similar pools of N than conventional soils. These pools of N not only related to the mineral forms of N and fertilizer inputs but also to the abundance of legumes, the potentially mineralizable N, and to plant production (Table 5). The decreases in potential N mineralization per unit of soil organic C or N indicated higher stability of N pools in organically managed soils. Microbial communities adapted to soils enriched with organic C, with highly stabilized N pools, may be a key element to mobilize these N pools. Indeed, some authors have reported a strong influence from the farm management history on soil microbial communities (Stark et al., 2008). In unfertilized legume intercrops it has been shown that decreased C/N ratio of particulate organic matter associated to the presence of legumes can increase the availability of N (Beedy et al., 2010). This is in agreement with the positive relationships found between N mineralization and legume abundance in our organically managed soils. However, the addition of composted manures showed the opposite trend as the N mineralization increased with the C/N ratio (Table 5). This may suggest that the forms of N added in composted manures of low C/N ratio are more stable that those resulting from legume crops.

However, other field studies on compost additions have found increased nitrification rates after the application of composted dairy waste (Habteselassie et al., 2006). In contrast, we found that N mineralization in soils amended with stabilized manures was always lower than in soils amended with labile N forms and mineral N. This low N availability may be the cause of the low plant growth in organically managed soils. Interestingly, this difference in plant production vanished when considering the four localities with the highest inputs of stabilized manures despite the fact that potentially mineralizable N was still lower when compared to their respective conventionally managed paired plots (data not shown). This may suggest that N availability was sufficient in these soils.

Both soil C and N stocks played a significant role with respect to plant productivity only in organically managed soils (Tables 4 and 5). As has been stated by other authors, soil fertility management in organic farming systems must rely on organic matter and on organic matter–dependent properties (Watson et al., 2002). Organic farming systems generally show less mineral N in soils. Under these conditions, mineralization processes may be the main source of N to crops. Changes in soil aggregation associated with increased C stocks can also favor plant productivity in soils amended with stabilized manures.

Conclusions

The greater retention of organic carbon in organically managed soils may be attributed to the greater recalcitrance and/or physical protection of the newly incorporated organic matter and to the prevention of the priming effect when applying stabilized manures. The N retention was high in all farming systems and was mainly driven by the quantity of N inputs and by the pool of mineral N. In organically managed soils N mineralization was favored by the use of legumes and by the application of composted manures with high C/N ratio. In organically managed soils the soil organic matter reserve was important for crop productivity. This may be related to the enhancement of N cycling and/or to the changes in soil structure associated with the use of stabilized manures and with the use of legumes in crop rotations.

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