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Implications of Cereal-Based Crop Rotations, Nitrogen Fertilization, and Stubble Grazing on Soil Organic Matter in a Mediterranean-Type Environment

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Abstract: Soil organic matter (SOM) is essential to all soil processes that have an impact on crop production and the environment. Soils of the semi-arid Mediterranean region are low in SOM due to environmental conditions (temperature, moisture) and centuries of cultivation. Hence, as SOM has a major influence on soil aggregation, nutrient supply, and soil moisture, as well as the relationships between them, there is a need to assess the impact of cropping systems on this critical soil parameter. During a 14-year rotation trial of durum wheat with alternate crops in northern Syria (mean annual rainfall: 340 mm), we examined the effects of common rotations, fertilizer nitrogen (N), and variable grazing of cereal stubble on SOM by measuring organic C in soil samples (depth: 0-20 cm) during October-November, before planting. The rotations significantly influenced mean SOM level, the order being fallow (lowest), continuous wheat, lentil, chickpea, vetch, and medic (highest). The mean effect of N was to increase SOM, but grazing intensity tended to decrease SOM. While results from different aspects of the trial published elsewhere demonstrated the value of legume-based rotations as biologically and economically viable alternatives to fallow or continuous cropping, this soil sampling SOM study showed that crop production can be compatible with the goal of improving soil quality, with potential environmental benefits. Thus, soil and crop management practices involving appropriate rotations (legumes/cereals), adequate N fertilization of the cereal crop, and retention of crop residues can combine sustainable and economic cropping while reversing soil degradation.

Key Words: Mediterranean environment, crop rotations, soil organic matter, organic carbon, cereal stubble grazing, nitrogen fertilization, rainfed cropping

Introduction

With the world's population currently at unprecedented levels, major global concerns of the 21st century include food security, soil degradation due to land misuse and soil management, and anthropogenic increases in atmospheric greenhouse gasses. As available land area per capita decreases, a major planetary challenge is to sustainably use the world's soil and water resources (Lal, 2000). The extent to which any ecosystem can withstand land-use pressure, or its resilience or potential to recover from a degraded state, is a function of the ecosystem in question, with semi-arid and arid regions being particularly vulnerable (Stewart and Robinson, 1997). The extent to which any land can be continuously farmed depends on the physical, chemical, and biological qualities of the soil.

The lands of the Middle Eastern region, which have been cultivated for millennia, are particularly fragile due to soil and climatic conditions unique to the Mediterranean areas (Kassam, 1981). Drought is a constant constraint to dryland farming in the Mediterranean ecosystem. Rainfall during the wet season (late autumn to early spring) is relatively low, normally ranging from 200 to 600 mm; there is also considerable inter-annual and within-season variability (Harris, 1995). Soils in the Near East are inherently low in nutrients, particularly nitrogen (N) and phosphorus (P), and are shallow, all impacting on root growth and soil moisture reserves (Ryan, 2002). Soil organic matter (SOM), which is a determining factor for soil quality, is low in soils of the Mediterranean-west Asia region (Ryan, 1998) and is a factor that promotes soil erosion by wind and water

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(Lal, 2002). The farming systems that have evolved to cope with drought center around rainfed cereal cropping, with wheat (*Triticum* spp.) being grown mainly in areas with higher rainfall and barley (*Hordeum vulgare*) in drier areas. The use of fallow in alternate years has been a traditional practice to conserve moisture and obtain acceptable yields in the cropped year (Cooper et al., 1987). Increasingly, because of land-use pressure, fallow is giving way to monoculture (Ryan, 2002). Consequently, long-term trials at the International Center for Agricultural Research in the Dry Areas (ICARDA) in northern Syria sought to find alternative crops to those currently grown in rotation with cereals as a substitute for fallow and continuous cereals, which is unsustainable (Harris, 1995).

Despite the well-known benefits of rotation, in terms of breaking disease cycles and improving soil quality (Karlen et al., 1994), the practice of fallowing has declined in the Middle East; however, research from the region has shown the benefits of legume-based rotations on crop water-use efficiency (Harris, 1994, Pala et al., 2007) and improved soil aggregation (Masri and Ryan, 2006). Recent emphasis on conservation tillage (Blevins and Frye, 1993) suggests synergistic benefits when combined with rotational cropping (Pala et al., 2000; Bessam and Mrabet, 2003); however, rotational benefits are slow to manifest themselves and can only be assessed by monitoring crop yield trends, as well as SOM, and chemical and microbial activity over a period of several years (Halvorson et al., 2002). Indeed, many studies of common cereal-based rotations (Yau et al., 2003) have only considered crop yields, with no consideration of the below-ground effects of rotations.

The extensive rotation trial (Harris, 1995) that provided conditions for the soil sampling study described herein was one of several long-term trials established by ICARDA (Ryan and Abdel Monem, 1998). As crop residues, i.e. cereal stubble or cut straw are also an integral part of rotations, in addition to fertilization, the long-term effect of these factors, within the context of the commonly practiced rotations, were assessed in terms of their effect on SOM. Thus, we systematically sampled the topsoil (depth: 0-20 cm) in the fall (October-November) before the normal crop planting season and measured organic carbon as an index of SOM. In some plots, the soil was sampled to a depth to 1 m in order to determine the profile distribution of SOM.

Materials and Methods

Soil Type

The study was conducted at Tel Hadya (lat 36°01´N, long 36°56´E; elevation: 284 m), the main station of the International Center for Agricultural Research in the Dry Areas (ICARDA), located about 30 km south of Aleppo, in northern Syria. The soil at the station is typically Mediterranean. The 23-ha area of the trial varied in soil depth from 0.5 to > 2.0 m above bedrock or parent material and is classified as fine clay, thermic Calcixerollic Xerochrept, merging into a Chromic Calcixerert (Ryan et al., 1997). The soil profile was calcareous throughout, with soil pH relatively constant at 7.9-8.1. Organic matter was normally between 1.0% and 1.2% in the top 20 cm, decreasing with depth. Cation exchange capacity ranged between 45 and 55 C mol kg^{-1}. Bulk density values ranged from 1.1 to 1.2 g cm^{-3} in the surface to 1.30 g cm^{-3} at a depth of 70-80 cm. Field capacity was around 40% and available moisture was between 15% and 17%.

Rotations

In all, 7 cropping sequences reflected the range of cereal-based rotations commonly practiced in the Mediterranean region, i.e. durum wheat (*Triticum turgidum* var *durum*) grown in rotation with lentil (*Lens culinaris* Medik.), chickpea (*Cicer arietinum*), pasture vetch (*Vicia sativa*), pasture medic (*Medicago* spp.), watermelon (*Citrullus vulgaris*) as a summer crop when residual moisture was adequate, clean-cultivated fallow, and continuous wheat. Both the cereal and the alternative phase were in place each year. With rotations being the main plots, secondary treatments involved N applied to the cereal phase at 0, 30, 60, and 90 kg N ha^{1}. The tertiary treatments involved grazing of the stubble by sheep at 3 intensity levels based on flock size (zero grazing or stubble retention, medium, and heavy grazing in which all the residues were removed). The rotations were established in 1983/84, followed by application of N and stubble grazing treatments within the rotation plots in 1985/86. The trial continued to completion in 1997/98. The design was a split-strip plot with 3 replications, with rotations as the main plots (36 × 120 m), N as sub-plots (36 × 30 m), and grazing as the sub-sub-plots (12 × 30 m). In essence, each of the 3 blocks or replications had 7 large rotation plots that were divided into 4 N levels, and each of these plots was further subdivided into smaller plots after harvest so that the grazing treatments could be superimposed.

Trial Management

Primary tillage involved a tined cultivator and spike-toothed harrow for seedbed preparation in the wheat phase, followed by seed drilling with 17.5-cm row spacing. No-till direct drilling was applied for the alternative crop phase (lentil, vetch, chickpea, and wheat) with 30-cm row spacing. Wheat and legumes were normally planted in the second half of November and early-mid December, respectively, following the initial seasonal rains. Watermelon was sown in mid-April on the land fallowed since wheat harvest, when the wetting front in the soil profile reached a minimum depth of 75-90 cm. Other management details regarding varieties, seeding rates, crop harvesting, and grazing are in Harris (1995). In brief, the durum wheat was a common Syrian type, Cham 1, seeded at 120 kg ha^{-1} with combine harvesting in June. For the other crops, local or common varieties were used. A basal P fertilizer application rate was applied to all plots at planting to ensure that Olsen P values were adequate and above the critical level for sufficiency (10 mg kg^{-1}), while the variable N application (0, 30, 60, and 90 kg ha^{-1}) was applied as half at planting and half at tillering in spring. Grazing of the stubble (no grazing or stubble retention, and medium and heavy grazing) was arranged by fencing the sub-sub-plots and using a large flock of sheep for 1 or 2 days. The main focus of this paper is the influence of the 3 variables (rotations, N fertilization, and stubble grazing) on SOM.

Climatic and Soil Parameters

Various weather measurements were recorded at an adjacent weather station, including daily rainfall and its distribution, maximum and minimum temperatures, class A pan evaporation, relative humidity, and wind speed. Soil measurements, following standard procedures (Ryan et al., 1997), included available water using a neutron probe (gravimetrically for surface layer, i.e. 0-15 cm) and a pressure-membrane apparatus, limited measurements of bulk density (based on soil weight in relation to the volume of the sampling augur head), and an array of soil chemical tests, e.g., organic matter, total N, ammonium (NH_4) and nitrate (NO_3), and available P (Olsen) at the beginning of each cropping season prior to sowing during October-November.

Statistical Analysis

We followed the statistical analysis procedures for long-term rotation trials as described by Jones and Singh (2000). The total variation was partitioned into a number of strata generated by the experimental design, representing plot totals and plot × year totals. The year-factor was further partitioned into 2 factors, series and cycle, so that the interaction of a treatment factor, e.g., rotation with cycle represents a cumulative build-up of effects as the rotation repeats. Similarly interactions of 2 or more treatment factors, e.g. rotation, N, and residues with cycle give cumulative build-up of interactions over time. The partitioning of the total sum of squares was carried out to produce the analysis of variance using commands from GenStat statistical software.

Weather Conditions

As is typical of Mediterranean climatic conditions (Kassam, 1981; Cooper et al., 1987), the 2 main weather components (temperature and rain) varied considerably throughout the 14-year cropping period, especially rainfall. Total seasonal rainfall the first 2 years after the ancillary treatments were applied (1985/86, 1986/87) was relatively normal, while the 1987/88 season's rainfall was the highest recorded, 503 mm. The next 3 seasons had below-average rainfall, particularly 1988/89 (235 mm) and 1989/90 (221 mm). Subsequent years, particularly 1992/93, 1994/95, and 1995/96, had above-average rainfall, with other years being close to average. Erratic seasonal distribution was common, particularly in 1988/89 when no effective rainfall occurred after December; similarly, though seasonal rainfall in 1993/94 was above average, its distribution was abnormal. Temperatures can be below freezing in winter and over 40 °C in summer. On average, ambient temperature had an inverse relationship with rainfall, with the lowest temperatures coinciding with the period of maximum rainfall in January-February, and frequently high temperatures occurring during grain-filling when rainfall tapers off.

Results

SOM was not only significantly influenced by the rotations, but also by rotations the within phases, i.e. cereals and alternative crops. In addition, the other main factors, N and residue grazing, also had significant influences on SOM; however, none of the 2-way interactions between rotations and N, or between rotations and residues were significant, except the N × residues interaction, which was significant at the 0.05 level. Similarly, the interactions between rotations and time (years) of the trial were significant.

In view of the significance of rotations and phases, the means of both phases are presented in terms of SOM data in Table 1 and overall rotation means are in parentheses. A clear pattern emerged for rotations and phases. SOM levels were affected by rotations in the following order: fallow (lowest), melon (essentially the same as fallow as it was only grown in 4 of the 12 seasons, leaving the plots in a fallow condition), continuous wheat, lentil, chickpea, vetch, and medic (highest, 1.32% SOM on average). The differential influence of phase was reflected in the higher SOM values in the alternative phase of the rotations with relatively low SOM (< 1.20%), but no difference between phases at the higher SOM levels in the vetch and medic rotations was observed.

The mean influence of time or advancing years of the trial is presented in Table 2, beginning with 1989 when SOM measurements were first made to the least year of the trial at the beginning of the 1997/98 cropping season. With the exception of 1992, there were no consistent differences between years, up to 1994. The higher SOM values in the 2 phases in 1992 are attributed to the fact that sampling in that year was inadvertently performed at a depth of 15 cm instead of the normal 0-20-cm depth. Despite the variation that existed between the last 3 years, the overall mean values were relatively constant at 1.22%-1.24%.

The influence of the individual rotations was relatively consistent, but trends with time were less consistent (Table 3). While the general trend was for SOM to increase with time in most rotations, there was considerable variation between years. Nevertheless, most rotations seemed to have reached a plateau in the last 4 years. While fallow tended to level out at about 1.12% SOM, the continuous wheat rotation tended to increase, as did chickpea (from 1.09% in 1989 to 1.27% in 1997). The vetch SOM reached a plateau in 1995, with no change thereafter, while medic seemed to have reached a higher level plateau.

As N had a highly significant effect on SOM levels in the trial, overall mean values are presented (Table 4). Thus, as N application rates increased, i.e. from 0 to 30, 60, and 90 kg N ha^{-1}, the corresponding values for SOM were of a similar order, i.e. in the unfertilized control to 1.13%, 1.19%, and 1.20% SOM for the 3 levels of N

Table 1. SOM, as influenced by the phases and means (in parentheses) of the rotation.

Rotation	Phase	Organic Matter	Rotation	Phase	Organic Matter
		%			
Fallow	Wheat	1.04 (1.07)	Melon[1]	Wheat	1.06 (1.07)
	Fallow	1.11		Melon	1.08
Wheat	Wheat	1.10 (1.12)	Vetch	Wheat	1.21 (1.21)
	Wheat	1.14		Vetch	1.21
Lentil	Wheat	1.07 (1.13)	Medic	Wheat	1.33 (1.32)
	Lentil	1.19		Medic	1.32
Chickpea	Wheat	1.15 (1.17)			
	Chickpea	1.20			
SEM		0.03			
Same Phase		0.02			

[1] Melon grown only in summer 4 out of the 12 years due to insufficient residual moisture in the soil profile.

SEM: Standard error of means.

Note: I % SOM is equivalent to 220 t of SOM ha^{-1}, assuming a bulk density of 1.1 g cm^{-1}. For comparison of values, 0.01% is equivalent to 2200 kg ha^{-1}.

Table 2. Overall mean effect of rotations (in parentheses) and phases (wheat, alternative) in relation to SOM according to years of the trial.

Year	Rotation/Phase	Organic Matter	Year	Rotation/Phase	Organic Matter
		%			
1989	Wheat	1.04 (1.10)	1994	Wheat	1.29 (1.17)
	Alternative	1.16		Alternative	1.06
1990	Wheat	1.16 (1.10)	1995	Wheat	1.11 (1.22)
	Alternative	1.05		Alternative	1.33
1991	Wheat	1.02 (1.08)	1996	Wheat	1.26 (1.23)
	Alternative	1.15		Alternative	1.20
1992	Wheat	1.30 (1.23)	1997	Wheat	1.22 (1.24)
	Alternative	1.15		Alternative	1.25
1993	Wheat	1.02 (1.10)			
	Alternative	1.17			

Values in parentheses represent means of the 2 phases.

Note: I % SOM is equivalent to 220 t of SOM ha^{-1}, assuming a bulk density of 1.1 g cm^{-1}. For comparison of values, 0.01% is equivalent to 2200 kg ha^{-1}.

Table 3. Overall effect of rotation on SOM concentration (%) according to years of the trial.

Year	Fallow	Melon	Wheat	Lentil	Chickpea	Vetch	Medic	LSD
1989	1.03	1.02	1.06	1.12	1.09	1.13	1.26	0.06
1990	1.00	-	-	-	1.11	-	1.22	-
1991	1.03	1.02	1.0	1.09	1.07	1.14	1.21	0.15
1992	1.22	-	1.20	-	1.25	-	1.44	-
1993	0.98	0.97	1.01.	1.05	1.12	1.12	1.23	0.15
1994	1.12	1.08	1.14	1.11	1.20	1.19	1.39	0.11
1995	1.11	1.11	1.17	1.13	1.23	1.32	1.46	0.08
1996	1.10	1.15	1.19	1.27	1.25	1.30	1.32	0.11
1997	1.12	1.16	1.25	1.16	1.27	1.28	1.39	0.14

LSD (SE) for comparing rotation was 0.01 for all years, except 1990 (0.15) and 1992 (0.20).
Note: I % SOM is equivalent to 220 t of SOM ha^{-1}, assuming a bulk density of 1.1 g cm^{-1}. For comparison of values, 0.01% is equivalent to 2200 kg ha^{-1}.

Table 4. SOM concentration in relation to N fertilizer application rates and stubble grazing intensity.

Nitrogen Fertilizer kg ha^{-1}	Organic Matter^{-1} %	Stubble Grazing	Organic Matter^{-1} %
0	1.12	None	1.20
30	1.13	Medium	1.15
60	1.19	High	1.14
90	1.20		
SEM+/-	0.0096		0.0046

Note: I % SOM is equivalent to 220 t of SOM ha^{-1}, assuming a bulk density of 1.1 g cm^{-1}. For comparison of values, 0.01% is equivalent to 2200 kg ha^{-1}.

fertilizer. As the level of grazing, or residue removal, increased, the mean SOM level declined; the difference was especially apparent between the no-grazing treatments in which the stubble was retained to the medium level of grazing.

Allowing for the anomalous year of 1992, there was a consistent increase in SOM values with each level of N application as the years of the trial progressed (Table 5); however, the change over time varied with the level of N. The unfertilized control and the lowest N level (30 kg ha^{-1}) appeared to reach a plateau of about 1.20% from 1995 to 1997, while the medium N level (60 kg ha^{-1}) leveled out at around 1.25%. The SOM values at the highest N level showed a consistent increase during the last 3 years of the trial. As the interaction between stubble grazing intensity and N application was significant, overall mean data for the 2 factors are presented (Table 6). While the trend of declining SOM values with grazing intensity was still apparent at each level of added N, the decline was less pronounced due to added N.

Although virtually all the data presented for SOM were from surface samples, the depth-wise distribution of SOM in a few rotational plots showed distinct differences due to the rotation. For example, in one of the medium-grazing plots the SOM values from the medic-rotation were not only higher in the top 0-20 cm of soil, but the differences between it and the other rotations persisted down to a depth of at least 60 cm. The slight increases in SOM obtained from the chickpea and continuous wheat rotations, compared to fallow, which was always lowest, did not persist below 20 cm.

Table 5. Mean effect of N fertilizer application rates (across all rotation and grazing treatments) on SOM concentration during the trial.

	Fertilizer N, kg ha^{-1}				
Year	0	30	60	90	LSD (5%)
	%				
1989	1.06	1.07	1.12	1.14	0.04
1990	1.06	-	-	1.16	-
1991	1.05	1.08	1.11	1.11	0.03
1992	1.21	1.25	1.30	1.35	-
1993	1.03	1.04	1.10	1.11	0.04
1994	1.13	1.15	1.21	1.21	0.05
1995	1.20	1.18	1.26	1.26	0.04
1996	1.18	1.20	1.26	1.27	0.04
1997	1.21	1.21	1.24	1.28	0.04

LSD (5%) for comparing the level of N was 0.048 within each given year, except 1990 (0.043) and 1992 (0.07).

Note: l % SOM is equivalent to 220 t of SOM ha^{-1}, assuming a bulk density of 1.1 g cm^{-1}. For comparison of values, 0.01% is equivalent to 2200 kg ha^{-1}.

Table 6. Mean effect of N fertilizer application rates and stubble grazing intensity (across all rotations) on SOM concentration.

Nitrogen	Stubble Grazing Intensity		
kg ha^{-1}	Zero	Medium	High
	%		
0	1.14	1.13	1.09
30	1.16	1.13	1.12
60	1.21	1.17	1.17
90	1.23	1.19	1.17

Note: l % SOM is equivalent to 220 t of SOM ha^{-1}, assuming a bulk density of 1.1 g cm^{-1}. For comparison of values, 0.01% is equivalent to 2200 kg ha^{-1}.

Discussion

When the cropping systems long-term rotation trial was initiated, the primary focus was sustainable cropping, in terms of cereal yields (Harris, 1995), as well as maximizing water-use efficiency (Harris, 1994). The issue of soil C in relation to climatic change had not yet emerged (Lal., 2001, 2002), although the relationship between SOM and crop rotations was well recognized (Karlen et al., 1994), especially in terms of soil quality. In recognition of the new emphasis on soil C or SOM, and that crop/soil management in relation to soil carbon storage could only be assessed in long-term trials (Clapp et al., 2000), sampling for SOM on a yearly basis was introduced mid-way through the trial. Notwithstanding the absence of baseline data from the individual plots at the start of the trial in 1983/84, it was clear that after 6 years significant changes were induced by the rotations, especially those involving the forage legumes, vetch and medic.

With the exception of work in Morocco, which was primarily focused on tillage systems in cereal rotations (Mrabet, 2000; Mrabet et al., 2001; Bessam and Mrabet, 2003), the present study is the first comprehensive rotation trial involving the range of rotations commonly practiced in the region to show the beneficial effect of the rotations on SOM. Earlier work in Syria from a grazing management trial reported that SOM increased in rotations with the same medic and vetch, but that it decreased with the stocking rate (White et al., 1994). Few studies, however, have considered the effect of variable stubble grazing on SOM status. Although legumes in rotation generally increase SOM, this depends on the legume in question. For instance, in Australia, Whitebread et al. (2000) found that lucerne (*Medicago sativa*) increased SOM, but neither chickpea nor barrel medic did.

While the accumulation of SOM from rotations is attributed to cropping intensity (Franzlubbers et al., 1994) and to the amount of residues from any particular rotation returned to the soil, the persistence of SOM in the soil can also be influenced by the nature of the legume root system, or its biochemical recalcitrance (Puget and Drinkwater, 2001). As neither an assessment of the total residues returned to the soil in our rotations nor any examination of the nature of the root systems were made, one cannot specifically pinpoint the basis for the observed increase in SOM from the forage legumes. Of particular interest was the observation that the benefit to SOM of some crops in a rotation is not confined to the surface layer, but, in the case of medic, extends well into the soil, reflecting the deep rooting system of this forage legume.

Regardless of the basis for SOM accumulation, it is essential that any crop in a rotation be economically and biologically compatible with the cropping system. Nonetheless, despite the benefits of medic, in terms of SOM, it is unlikely to be adopted into Middle Eastern agriculture (Christensen et al., 2000), in contrast to vetch, which has much better prospects (Jones and Singh, 2000). For the food legumes, chickpea and lentil, which are very much parts of the cropping system in the Mediterranean region, the slight increase in SOM was an added bonus. Despite increases in continuous cropping of cereals in terms of SOM, the practice is unsustainable.

In contrast to the other crops in the rotations, fallow, despite giving the highest yields in the cropped year, showed the lowest level of SOM. Decreases in SOM in fallow have been observed in other studies (Halvorson et al., 2002), an effect that is generally attributed to the mineralization of the cereal roots and residues in the fallow year, as moisture and aerobic conditions favor the process during a time when no additional carbon in the form of a growing crop is put into the soil. By comparison with fallow, annual cropping not only reduces the decline in SOM associated with tillage, but also stimulates soil microbial activity (Collins et al., 1992).

While the secondary treatments within the long-term trial were not as pronounced as the rotation effect, there were, nonetheless, significant effects. The consistent increases in mean SOM with increased rates of N fertilizer application are probably attributable to increased root biomass associated with higher yields (Ryan et al., 1999). In other studies, the effect of added N was either variable (Salinas-Garcia et al., 1997) or not observed (Halvorson et al., 2002).

Cereal-based rotations cannot be fully evaluated without considering the residues, i.e. the straw that is left on the ground or the stubble standing after harvest. Under Middle Eastern conditions stubble and straw on the ground are grazed bare by flocks of sheep (Cooper et al., 1987). The experimental conditions of our trial simulated the actual grazing condition on the plots that were intensively grazed. The medium-grazed plots did not reflect reality, though they were experimentally interesting. The stubble retention treatment was more hypothetical and predictive of conservation agriculture, which is not yet applicable in the region.

Nonetheless, as one might expect overall SOM levels declined with the progression from no grazing to heavy grazing. Though the amount of straw incorporated into the soil under the conditions of our study was low, the build-up of SOM was small and gradual. Other studies have shown the connection between crop residues returned to the soil by cultivation and the soil's organic matter content (Franzlubbers et al., 1994). Based on the positive relationships between total SOM, and the more biologically reactive biomass, labile carbon, and N fractions (Collins et al., 1992; Salinas-Garcia et al., 1997), the impact of residues under Mediterranean conditions is likely to be more pronounced than suggested by gross SOM values.

The data gathered from this comprehensive long-term rotation trial, including the soil parameters, is very encouraging. While SOM levels for some rotations appeared to plateau, the intriguing question that remains is whether the final values from the last year of the trial represent the maximum equilibrium SOM value for these cropping conditions in a Mediterranean environment. Given the complex number of interacting factors in the trial, we conclude that it should have been continued for several more years, especially given the dearth of such trials in the Mediterranean region. Based on the models of West and Post (2002), such equilibria take longer to reach than the duration of our study.

The positive message this study offers is that not only are these cereal-legume rotations economically viable, they also can improve soil structure (Masri and Ryan, 2006) and sequester atmospheric C as well, thus helping to mitigate the adverse effects of greenhouse gasses (Falloon and Smith, 2003). Given the extent of drylands throughout the world (Lal, 2002), any modest increase in soil C from cropping would have a major impact on global C sequestration.

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