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RESEARCH ARTICLE

Nitrogen fertilization enhances soil quality in the short-term in irrigated intensified maize systems

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Abstract

Aim of study: This study had a double objective that consisted of: (i) assessing the effects of N fertilisation on soil quality under different cropping systems (monocropping vs. double-annual cropping systems) under irrigated maize conditions; and (ii) identifying soil parameters related to soil quality that respond quickly to short-term management changes in Mediterranean irrigated maize systems.

Area of study: Zaragoza province, Spain

Material and methods: The field experiment involved a strip plot design with three growing systems –maize monoculture (MM), pea-maize (PM), and barley-maize (BM)– and three fertilisation levels: unfertilised (0N), medium nitrogen (MN), and high nitrogen (HN). After two years, soil samples were collected at two depths (0-10 cm and 10-30 cm). Soil parameters measured related to soil quality were total soil organic carbon (SOC), water-stable macro aggregates (WSM), macroaggregate C concentration (Macro-C), particulate organic matter carbon (POM-C), permanganate-oxidisable organic carbon (POxC), soil microbial biomass carbon (MBC), and enzyme activity: dehydrogenase (Dhns) and ß-glucosidase (Gds).

Main results: Our research showed that in intensified systems, the highest fertilisation rate improved soil parameters in the topsoil by enhancing all the soil parameters tested except for the dehydrogenise enzyme activity. In contrast, in the monoculture, the highest fertilisation rate only increased SOC and Macro-C. Fertilisation had a higher impact on soil quality in the BM system compared to the PM system, probably related to greater quantities of crop residues in the BM system under a high fertilisation rate.

Research highlights: Nitrogen fertilisation improves soil parameters related to soil quality in intensified systems and the magnitude of the fertilisation impact may depend on crop species and residues. The impact of N fertilisation on soil quality can be detected in the short term when testing early indicators of soil quality.

Keywords: cropping diversification, double-annual cropping systems, enzyme activities, irrigated maize, Mediterranean agroecosystems, nitrogen fertilization, soil organic carbon.

La fertilización nitrogenada aumenta a corto plazo la calidad del suelo en sistemas intensificados de maíz en regadío

Resumen

Objetivo del estudio: Este estudio busca un doble objetivo que consiste en (i) evaluar los efectos de la fertilización nitrogenada en diferentes sistemas de cultivo (monocultivo vs sistemas de doble cultivo) en la calidad del suelo de un sistema de maíz en regadío; e (ii) identificar parámetros de calidad del suelo con respuesta rápida ante cambios a corto plazo en sistemas mediterráneos de maíz en regadío.

Área de estudio: Provincia de Zaragoza, España

Material y métodos:: El diseño experimental fue un *strip plot* con tres sistemas de cultivo: monocultivo de maíz (MM), doble cultivo guisante-maíz (PM) y doble cultivo cebada-maíz (BM) y con tres dosis de fertilización: sin fertilizar (0N), media (MN) y alta (HN). Después de dos años de estudio, se muestreó el suelo a dos profundidades (0-10, 10-30 cm). La calidad del suelo se determinó analizando carbono orgánico del suelo (SOC), macroagregados estables al agua (WSM), carbono de los macroagregados (Macro-C), carbono orgánico particulado (POM-C), carbono orgánico oxidable al permanganato (POxC), carbono de la biomasa microbiana (MBC) y actividad enzimática (deshidrogenasa, Dhns; y ß-glucosidasa, Gds).

Principales resultados: Nuestra investigación mostró que los sistemas intensificados con altas dosis de fertilización nitrogenada mejoraron la calidad del suelo en la capa más superficial, incrementando todos los parámetros medidos excepto la actividad enzimática de la deshidrogenasa. En cambio, en el monocultivo de maíz con alta dosis de fertilización sólo aumentó el SOC y el Macro-C. El impacto de la fertilización en la calidad del suelo fue mayor en el sistema BM comparado con el sistema PM, probablemente relacionado con un mayor contenido de residuos en el sistema BM con dosis de fertilización alta.

Aspectos destacados de la investigación: La fertilización nitrogenada mejora los parámetros relacionados con la calidad del suelo en sistemas intensificados. No obstante, este impacto puede depender de los cultivos seleccionados y la producción y calidad de los residuos de estos cultivos. El impacto de la fertilización en la calidad del suelo se puede detectar a corto plazo seleccionando indicadores tempranos de calidad del suelo.

Palabras clave: actividades enzimáticas, agrosistemas mediterráneos, carbono orgánico del suelo, diversificación de cultivos, fertilización nitrogenada, maíz en regadío, sistemas de doble cultivo.

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Introduction

Soil quality is a primary indicator of sustainable agricultural management (Doran, 2002) since it encompasses the ability of a soil to support crop growth without harming environmental quality (Karlen et al., 1997). A number of soil quality and health indicators are easy to find in the literature (Andrews & Carroll, 2001; Bünemann et al., 2018) and the ideal indicator should be informative, sensitive, effective, and relevant (Lehmann et al., 2020). One of the main indicators is soil organic carbon (SOC), due to its importance and the role it plays in many soil functions and ecosystems services (Nuneset al., 2021). However, SOC changes usually take time to occur and, thereby, increases and/or decreases are observed several years after any management change (Smith, 2004). Accordingly, it is interesting to evaluate and test other more rapid indicators that provide insight into soil carbon (C) changes in the short-term (Plaza-Bonilla et al., 2014), such as soil C fractions or soil biological properties (e.g., microbial biomass or enzyme activities) (Lehmannet al., 2020). Identifying selected soil quality indicators would allow optimal management practices to be adopted, especially in semiarid irrigated maize production areas in which rapid changes in certain soil properties have been observed after a shift in management practices (Álvaro-Fuentes et al., 2021).

In Mediterranean areas, irrigated maize is intensively managed with the associated elevated use of agriculture inputs (pesticides, fertilisers, tillage) and the continuous growth of maize as the main cropping system, with no crop diversification. Increased fertiliser use, particularly of nitrogen (N) fertilisers, is linked to high production costs and severe environmental problems, including greenhouse gas emissions (Franco-Luesma et al., 2020) and nitrate pollution (Berenguer et al., 2008). However, the effect of N fertilisation on SOC and associated C pools is not clear since it has been associated to both positive and negative effects on soil organic matter mineralisation (Mahal et al., 2019).

Likewise, the expected positive effect of N fertilisation on soil C inputs and, thus, on SOC storage is dependent on attaining the agronomic optimum N fertilisation rate (Poffenbarger et al., 2017). According to Poffenbarger et al. (2017), N rates above the agronomic optimum N fertilisation rate do not increase crop residue inputs, but may favour soil organic matter mineralisation due to the increase in soil mineral N.

One option which is gaining ground as a method for reducing the use of N fertilisers in irrigated maize systems in Mediterranean Spain is crop diversification, introducing N-fixing crops (Gabriel & Quemada, 2011). In this area, the majority of studies have been oriented at evaluating what agronomic impact the introduction of legumes as cover crops has, as a substitute for the typical bare fallow between maize seasons (Salmerón et al., 2010; Gabriel et al., 2012). However, less attention has been paid to evaluating the performance of double-annual cropping systems in which the system is intensified through the growth of two crops within the same year, involving the associated increased production and profitability per land unit (Maresma et al., 2019). Besides the agronomic performance, the impact of cropping system changes on soil quality parameters has also been evaluated but only in terms of cover crops for which positive impacts on SOC and C fractions (García-González et al., 2018), arbuscular mycorrhizal fungi (Hontoria et al., 2019) and soil microorganisms (Muñoz et al., 2007) have been reported. However, the impact of cropping intensification on other soil properties related to soil quality, such as soil enzyme activities, and in other systems besides cover crops (e.g., cropping intensification through double-annual cropping systems) is less studied in these irrigated maize systems (Maresma et al., 2019; Zugasti-López et al., 2024). Accordingly, this study had a double objective that consisted of: (i) assessing the effects of N fertilisation on soil quality under different cropping systems (monocropping vs. double-annual cropping systems) under irrigated maize conditions; and (ii) identifying soil parameters related to soil quality that respond quickly to short-term management changes in Mediterranean irrigated maize systems. Our main hypothesis was that the expected positive effect of N fertilisation on crop residue production would promote a short-term increase in soil parameter values related to soil quality.

Material and methods

Site characteristics and experimental design

The experiment was set up in Zaragoza, Spain (41º42′N, 0º49′W, 225 m altitude) in a Typic Xerofluvent soil (Soil Survey Staff, 2015). The air temperature, annual mean precipitation and annual reference evapotranspiration (ETo) of the experimental site are 14.1 ºC, 298 mm, and 1243 mm, respectively. The soil properties at the start of the experiment are shown in Table 1. The experiment was established in a 1 ha flood-irrigated field, historically managed (past 25 years) as irrigated maize and wheat (*Triticum aestivum* L.) monocultures. The alternation of the two monocultures over the 25-year period varied, but periods of at least 5 years were maintained. Prior to establishing the experiment, the field had been cultivated with a maize monoculture for four years. Crop residues had been kept in the field and incorporated through mouldboard ploughing (after wheat) or subsoiling (after maize). Fertilisation management consisted of the use of high N inputs, always in the form of mineral fertilisers. The typical N rates applied to the crops were about 350 and 200 kg N ha^{-1} for maize and wheat, respectively. The use of these elevated N rates is common in irrigated Mediterranean areas, especially for summer crops (Franco-Luesma et al., 2022).

In October 2018, the field was divided into three parts (0.33 ha each) and a different cropping system was established in each part: the traditional maize monoculture (MM), and two alternative double-annual cropping systems (pea-maize, PM; and barley-maize, BM). These two alternative cropping systems were selected to integrate cropping diversification together with cropping intensification. Thus, in the PM and BM systems, both crops (pea/maize and barley/maize) were successively grown within the same year. In all three cropping systems, three N fertilisation rates were compared (i.e., control or unfertilised, 0N; medium nitrogen rate, MN; and high nitrogen rate, HN) in plots of 6 x 25 m (150 m^2), using an experimental design of strip plots with three repetitions. There was, therefore, a total of twenty-seven 150 m^2 plots: 3 systems x 3 N rates x 3 repetitions.

Table 1. Main soil properties at the beginning of the experiment in September 2018, in Zaragoza, Spain.

Soil property	Soil depth (cm)	
	0-10	**10-30**
pH (H_2O, 1.25)	7.90	8.05
EC 1:5 (dS m^{-1})	0.33	0.25
CaCO3 eq. (%)	33.2	33.1
Particle size distribution (g kg^{-1})		
Sand (2000-50 µm)	196	194
Silt (50-2 µm)	616	616
Clay (<2 µm)	188	190

In terms of crop operations, long-cycle maize (FAO 700) was planted both years in the MM system, on 15 April, 2019, and 29 April, 2020, and harvested on 30 September, 2019, and 6 October, 2020, respectively. However, in the PM and BM systems, short-cycle maize (FAO 400) was planted on 25 June, 2019, and 17 June, 2020, and harvested on 10 December, 2019, and 24 November, 2020, respectively. In all three systems, maize was planted at an intensity of 89,500 plants ha^{-1}. In the MM system, the period between maize crops consisted of bare fallow with subsoiler ploughing in March and rotary tilling in April to prepare the maize seedbed. In the two alternative systems (PM and BM), pea and barley were sown on 26 October, 2018 (start of the experiment), and on 15 January, 2020, (after the maize was harvested) and harvested on 29 May, 2019, and 8 June, 2020, respectively, before the planting of maize. Disk harrowing followed by rotary tilling were performed before the pea and barley were sown. In 2020, after the harvesting of the pea and barley the seedbed was prepared for maize using rotary tilling. In 2019, the maize was planted directly over the pea and barley residue. The three N fertilisation rates (0N, MN and HN) were 0, 200 and 400 kg N ha^{-1} and 0, 125 and 250 kg N ha^{-1} for the maize and barley phases, respectively. In both of these crops, N fertilisation was split into two applications: pre-sowing as 8-15-15 fertiliser compound; and top-dressing as calcium ammonium nitrate (CAN 27%). In the pea phase of the PM system, only an 8-10 PK fertiliser compound was applied at pre-sowing.

All three cropping systems were flood irrigated. The total amount of water applied differed between the cropping systems and years, ranging from 743 mm (MM system in 2020) to 1,027 mm (PM and BM systems in 2019). The irrigation requirements were calculated based on precipitation and crop evapotranspiration as reported in Franco-Luesma et al. (2022).

Crop residue biomass and soil analyses

The aboveground crop residue biomass was measured at crop maturity for all three crops (maize, pea and barley) and during the two cropping seasons (2018-2019 and 2019-2020). For maize, in two areas per plot, all the plants included in 2-m-long rows were sampled. For pea and barley, also in two areas per plot, all the plants included in 0.25 and 0.2 m^2 were sampled, respectively. For all the samples, the grain was separated from the rest of the plant, oven-dried at 60ºC for 48 h and weighed.

In July 2021, soil sampling was performed at two soil depths: 0-10 and 10-30 cm. In each plot, samples were taken at two different points 10 m apart and mixed to obtain a composite soil sample per depth and plot. A total of 108 soil samples were therefore collected (27 plots, 2 soil depths and 2 observations per plot and depth). The soil samples were collected using a flat spade and carefully stored in air-tight containers for aggregate separation and plastic bags for the other measurements. During the field sampling and transportation to the laboratory, the plastic bags were stored in a cool-box. Once in the laboratory, the soil samples for aggregate separation were passed through an 8-mm sieve and air dried.

The soil samples in plastic bags were split into two subsamples. A first subsample for enzyme activities was kept in the freezer until analysis and a second subsample for C analyses was air dried and ground to pass through a 2-mm sieve.

Soil water-stable macroaggregates (> 250 µm) were isolated following an adapted method from Elliot (1986) in which a 100 g air-dried soil sample (< 8 mm) was submerged in deionised water for 5 min and then manually sieved through a 250 µm sieve for 2 min with a frequency of 25 movements per min. The water-stable macroaggregate (WSM) content was calculated as the relationship between the mass of aggregate retained in the sieve and the initial soil (100 g). A subsample of macroaggregates was used to measure the aggregate C concentration. The particulate organic matter carbon (POM-C) was isolated following Cambardella & Elliot (1992), where 20 g of soil was dispersed in sodium hexametaphosphate solution and later passed through a 53 µm sieve. The material that passed through that sieve was oven dried (50ºC) and the C concentration determined. Total SOC, aggregate C and C from the < 53 µm fraction were determined by dry combustion in a LECO RC-612 analyser (Leco Corp., St. Joseph, MI). The POM-C was calculated by subtracting the C in the < 53 µm fraction from the total SOC. The permanganate-oxidisable organic C (POxC) was measured according to Weil et al. (2003) in which absorbance was measured at 550 nm in soil mixed with a 0.2 M $KMnO_4$ solution. Soil microbial biomass C was measured using the substrate-induced respiration method (Anderson & Domsch 1978), where CO_2 production was quantified over a 24 h period in glucose-amended soils using a µ-Trac 4200 system (SY-LAB, GmbH P.O. Box 47, A-3002 Pukersdorf, Austria). Dehydrogenase and ß-glucosidase enzyme activities were analysed via iodonitrotetrazolium chloride determination (Von Mersi & Schinner 1991) and p-nitrophenol determination (Tabatabai 1982), respectively.

Statistical analyses

The main effects (N fertilisation and soil depth) and the results of their interactions on the different soil variables studied were evaluated using analyses of variance (ANOVA). The experimental design consisted of a strip plot design in which the N fertilisation was replicated three times but the cropping system was not replicated. The lack of replication in the cropping system prevented it being evaluated as a main factor and only the interaction between this factor and the other two factors (N fertilisation and soil depth) could be tested (Federer and King, 2007). The data was tested to meet ANOVA assumptions, homogeneity of variances and normality, using the Levene and Shapiro-Wilk tests, respectively. The post-hoc test Fisher's Least Significant Difference (LSD) was used when significant differences were found at the 0.05 level. To assess possible relationships among the measured variables the Pearson correlation analysis was used. The statistical analyses were performed using R software (R Core Team, 2017).

Results

The N fertilisation rate impacted the aboveground crop residue biomass but only in the two diversified cropping systems (Table 2). In the MM systems, the total crop residue biomass produced in the two growing seasons (2018-2019 and 2019-2020) was similar among the different N fertilisation rates. However, in the PM rotation the two fertilised treatments showed greater crop residue biomass than the unfertilised treatment (Table 2). In the BM rotation, residue production decreased in the order HN>MN>0N. Additionally, in the two intensified systems (PM and BM), the proportions of maize residue biomass in the two double cropping systems were 62 and 66% for the maize-barley and maize-pea systems, respectively (Table 2).

The analysis of variance of soil properties showed significant differences for the two main factors considered, soil depth and fertilisation N rate (Table 3). The soil depth affected all the soil properties studied, except for WSM. In all cases, the greatest values were always observed in the first 10 cm soil depth. The maximum difference between the two soil depths (0-10 and 10-30) was observed for the macroaggregate C in which the C content of the topsoil was 40% greater than at 10-30 cm depth. In the other soil properties, the difference between the two soil depths ranged between 10 and 24% (Table 3).

Table 2. Total aboveground crop residue biomass (in Mg dry matter ha^{-1}) under cropping system (MM, maize monoculture; PM, pea-maize rotation; and BM, barley-maize rotation) and N fertilization rate (0N, unfertilised; MN, medium N rate; HN, high N rate) treatments for each crop (maize, barley and pea) and year. The values between brackets are the deviation standard deviation.

Cropping system	**Crop**	**N fertilization rate**		
		0N	**MN**	**HN**
MM	2019 - Maize	16.27 (1.31)	15.11 (4.27)	17.34 (2.81)
	2020 - Maize	1.98 (1.03)	2.75 (0.75)	5.45 (2.13)
	Total 2 years	*18.25 (2.04)*	*17.86 (3.71)*	*22.79 (4.86)*
PM	2019 - Pea	5.63 (0.79)	7.22 (1.16)	6.38 (0.87)
	2019 - Maize	6.07 (2.86)	7.48 (2.85)	6.77 (1.00)
	2020 - Pea	2.13 (0.37)	1.70 (0.44)	1.74 (0.79)
	2020 - Maize	5.59 (1.47)	6.98 (1.47)	9.50 (1.30)
	Total 2 years	*19.42 (3.65) b* ‡	*23.38 (5.82) a*	*24.39 (3.21) a*
BM	2019 - Barley	4.55 (1.61)	4.98 (1.21)	6.95 (1.50)
	2019 - Maize	5.49 (2.56)	7.90 (0.49)	9.21 (3.22)
	2020 - Barley	1.51 (0.41)	4.15 (2.25)	4.30 (1.70)
	2020 - Maize	4.30 (0.33)	5.79 (0.60)	8.78 (2.01)
	Total 2 years	*15.85 (4.27) c*	*22.82 (2.01) b*	*29.24 (3.09) a*

‡ Within a cropping system, values followed by different letters indicate significant differences in total above-ground crop residue biomass for the 2 years among N fertilization rates at 0.05 level.

The N fertilisation rate affected macroaggregate C, SOC, POM-C, MBC, and the ß-glucosidase enzyme activity. These five soil properties were also affected by the soil depth, as were POxC and the dehydrogenase enzyme activity (Table 3). The unfertilised treatment (0N) showed the lowest SOC, POM-C, MBC and ß-glucosidase activity. However, in the case of macroaggregate C, the 0N and MN levels presented lower contents than with HN (Table 3). The WSM, POxC and dehydrogenase activity did not differ between N fertilisation levels. When the effect of the N fertilisation rate was analysed across cropping systems and for each soil layer, different trends were observed depending on the soil variable considered (Figs. 1 and 2). At the 0-10 cm soil depth, WSM, POxC and MBC were affected by the N fertilisation rate but only in the BM system, where the 0N rate always presented the lowest values (together with MBC in the case of BM) (Fig. 1). The POM-C and ß-glucosidase activity was affected by the N fertilisation rate in the two diversified systems (PM and BM). As before, in these two cropping systems the lowest POM-C and ß-glucosidase activity values were observed for the 0N rate (Fig. 1). The exception was the PM system, where both soil properties presented similar values for the 0N and the MN rates. The total SOC content showed differences in the MM monoculture and the BM rotation. In MM, the HN rate led to a 10% greater SOC content compared to 0N (Fig. 1). However, in the BM rotation, the SOC content in 0N was 17 and 22% lower than the MN and HN, respectively (Fig. 1). In the MM and PM systems, the C concentration of soil macroaggregates was significantly greater under HN than under 0N, this difference being almost two-fold in the case of PM (Fig. 1). The dehydrogenase activity was the only soil variable studied which did not present significant differences among N rates for any cropping system (Fig. 1). At the 10-30 cm soil depth, ß-glucosidase activity was the only soil variable to show significant differences between N fertilisation rates (Fig. 2). In particular, the differences in ß-glucosidase activity were only observed in the BM system, where the 0N rate showed the lowest enzyme activity with values close to 0.8 µmol *p*NP g-1 dry soil h^{-1} (Fig. 1).

Table 3. Analysis of variance of water-stable soil macroaggregates (WSM), macroaggregate C concentration (Macro-C), total soil organic carbon (SOC), particulate organic matter C (POM-C), soil permanganate-oxidisable organic carbon (POxC) concentration, soil microbial biomass carbon (MBC), dehydrogenase enzyme activity (Dehydrogenase), ß-glucosidase enzyme activity (Glucosidase) as affected by the soil depth, fertilisation rate (0N, unfertilised; MN, medium N rate; HN, high N rate) and the interactions between both factors and cropping system (System).

Treatments	**WSM**	**Macro-C**	**SOC**	**POM-C**	**POxC**	**MBC**	**Dehydrogenase**	**Glucosidase**
	(g g^{-1} soil)	**(g C kg^{-1} macroaggregate)**	**(g C kg^{-1} soil)**	**(g C kg^{-1} soil)**	**(mg C kg^{-1} soil)**	**(mg C kg^{-1} soil)**	**(µmol INTF g^{-1} dry soil h^{-1})**	**(µmol pNP g^{-1} dry soil h^{-1})**
Soil depth (cm)								
0-10	15.0	23.8 a‡	11.1 a	3.4 a	442 a	812 a	0.16 a	1.15 a
10-30	15.0	16.8 b	10.1 b	3.0 b	399 b	684 b	0.13 b	1.02 b
Fertilization N rate								
0N	14.6	16.7 b	10.0 b	2.5 b	398	665 b	0.14	0.90 b
MN	15.5	19.3 b	10.9 a	3.6 a	430	790 a	0.15	1.14 a
HN	14.8	24.9 a	10.9 a	3.5 a	434	788 a	0.14	1.22 a
ANOVA (p values)								
Soil depth (Depth)	ns	<0.001	<0.001	<0.01	<0.001	<0.001	<0.001	<0.01
Fertilization N rate (Fert)	ns	<0.01	<0.01	<0.05	ns	<0.01	ns	<0.01
System x Depth	<0.05	ns	ns	ns	ns	ns	ns	ns
System x Fert	ns	ns	ns	ns	ns	<0.05	ns	<0.05
Depth x Fert	ns	ns	ns	<0.05	ns	ns	ns	ns
System x Depth x Fert	ns	ns	ns	ns	ns	ns	ns	ns

ns, non-significant

‡ Values followed by different letters are significantly different at 0.05 level.

The WSM was affected by the interaction between the cropping system and soil depth (Table 3). Compared to the PM and BM systems, in the MM system the WSM at 10-30 cm soil depth was greater than at 0-10 cm (data not shown). Likewise, the POM-C was affected by the interaction between the N fertilisation rate and soil depth. The POM-C in the 0N treatment was similar between the two soil depths, unlike MN and HN in which greater POM-C was observed at 0-10 cm depth compared to 10-30 cm (data not shown) (Table 3).

The eight soil parameters studied together with the aboveground crop residue biomass showed significant positive Pearson correlation coefficients except for the relationship between aboveground crop residues and the macroaggregate C concentration (Table 4). There was no correlation between macroaggregate C and the following parameters: WSM, MBC, POM-C and the two enzyme activities (dehydrogenase and ß-glucosidase), nor in any of the relationships of the aboveground crop residue biomass with soil parameters, except for the relationship between crop residues and ß-glucosidase (Table 4). The highest coefficients were found in the relationship between SOC and POM-C (0.88) and between SOC and the ß-glucosidase enzyme activity (0.88). In contrast, the lowest significant coefficients were found in the relationships between aboveground crop residue biomass and ß-glucosidase, and between SOC and macroaggregate C, where the coefficients only reached 0.28 and 0.36, respectively (Table 4).

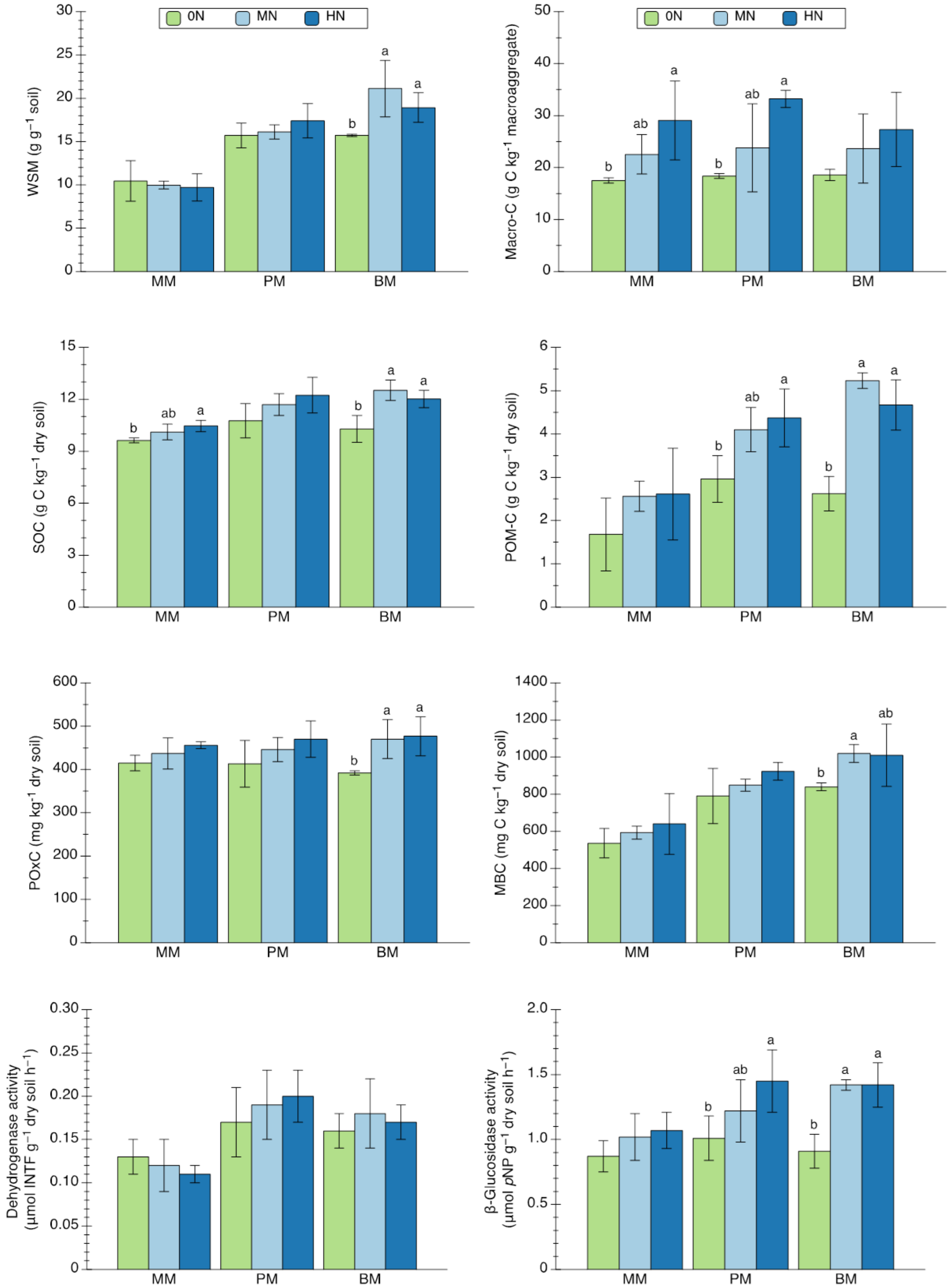

Figure 1. Water-stable macroaggregates (WSM); macroaggregate C content (Macro-C); soil organic carbon (SOC) content; particulate organic matter C (POM-C) content; permanganate-oxidisable organic C (POxC) content; microbial biomass carbon (MBC); dehydrogenase activity; ß-glucosidase activity as affected by the nitrogen fertilisation rate (0N, unfertilised; MN, medium rate; HN, high rate) for the three cropping systems (MM, maize monoculture; PM, pea-maize double system; and BM, barley-maize double system) for the 0-10 cm soil depth. Within a cropping system, values followed by different letters are significantly different at the 0.05 level. The vertical bars represent the standard deviation.

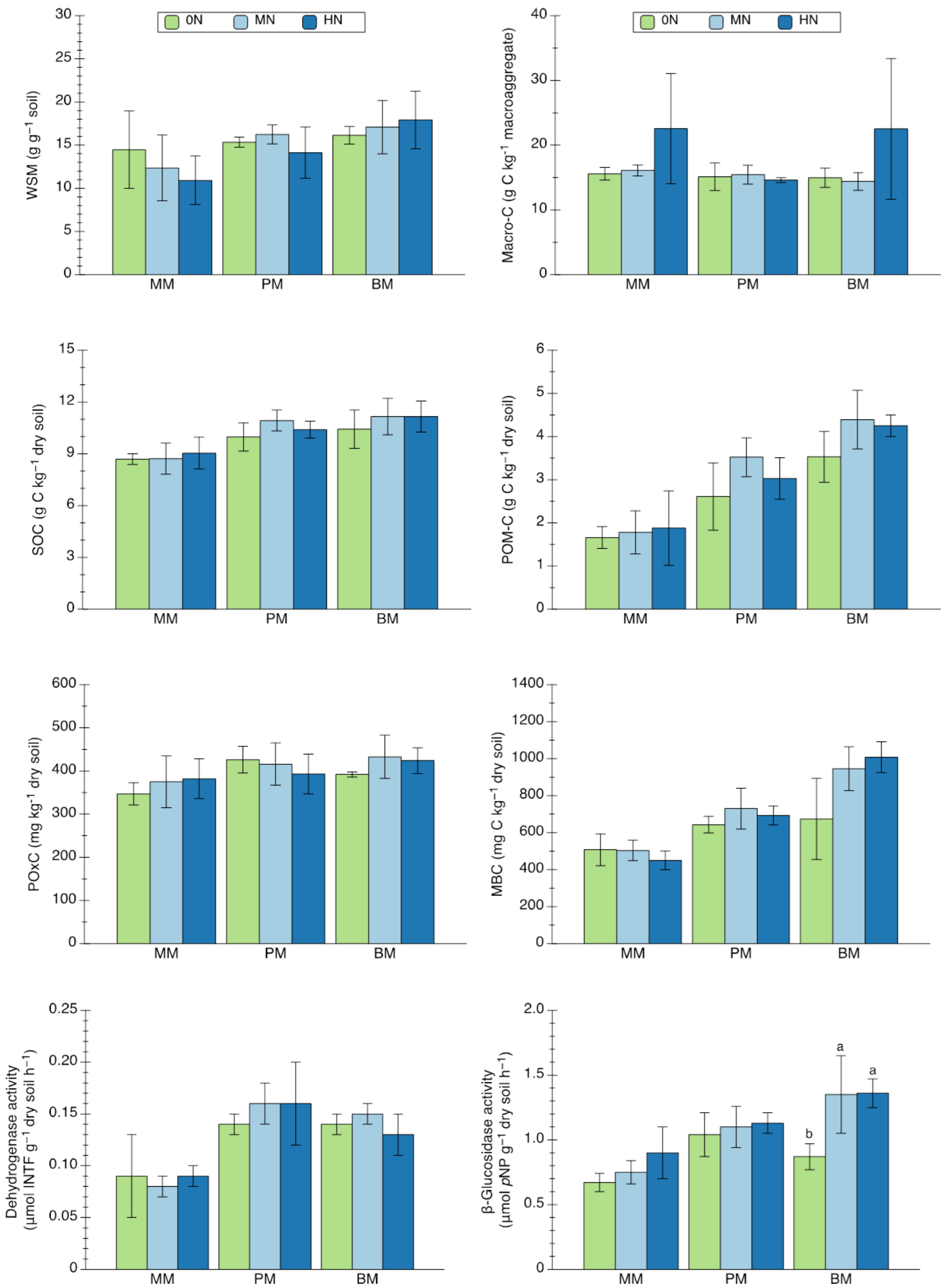

Figure 2. Water-stable macroaggregates (WSM); macroaggregate C content (Macro-C); soil organic carbon (SOC) content; particulate organic matter C (POM-C) content; permanganate-oxidisable organic C (POxC) content; microbial biomass carbon (MBC); dehydrogenase activity; ß-glucosidase activity as affected by the nitrogen fertilisation rate (0N, unfertilised; MN, medium rate; HN, high rate) for the three cropping systems (MM, maize monoculture; PM, pea-maize double system; and BM, barley-maize double system) for the 10-30 cm soil depth. Within a cropping system, values followed by different letters are significantly different at the 0.05 level. The vertical bars represent the standard deviation.

Table 4. Matrix of Pearson correlation coefficients for aboveground crop residue biomass (AbRes), water-stable soil macroaggregates (WSM), macroaggregate C concentration (Macro-C), total soil organic carbon (SOC), particulate organic matter C (POM-C), soil permanganate-oxidisable organic carbon (POxC) concentration, soil microbial biomass carbon (MBC), dehydrogenase enzyme activity (Dhns), ß-glucosidase enzyme activity (Gds). * Indicates statistically significant correlation ($p < 0.05$).

	AbRes	WSM	Macro-C	SOC	POM-C	POxC	MBC	Dhns	Gds
AbRes	1.00								
WSM	0.25	1.00							
Macro-C	-0.07	0.07	1.00						
SOC	0.23	0.63*	0.36*	1.00					
POM-C	0.27	0.65*	0.28*	0.88*	1.00				
POxC	0.15	0.43*	0.46*	0.73*	0.53*	1.00			
MBC	0.26	0.67*	0.26	0.79*	0.78*	0.50*	1.00		
Dehydrogenase	0.20	0.37*	0.18	0.59*	0.55*	0.41*	0.57*	1.00	
Glucosidase	0.28*	0.57*	0.32	0.80*	0.75*	0.70*	0.74*	0.53*	1.00

Discussion

This study, performed under irrigated Mediterranean conditions, demonstrates the short-term effect of N fertilisation in different cropping systems on soil properties related to soil quality. In general, it was observed that unfertilised treatments always tended to show lower soil property values compared to the two fertilised treatments (MN and HN). According to Geisseler and Scow (2014), mineral N fertilisation increases SOC levels and, concomitantly, soil microbial biomass, with SOC being a major factor controlling microbial growth and activity. In our experiment, the significant increase between the unfertilised and fertilised plots was not only observed for SOC and microbial biomass but also for other soil properties related to the C cycle (POM-C, Macro-C) and microbial activity (ß-glucosidase). Interestingly, in our study, the positive effect of N fertilisation on SOC, C fractions and related microbial activity properties relied on the cropping system established. Hence, the BM cropping system showed the greatest impact of N fertilisation on soil properties, followed by PM and, lastly, the monoculture (MM). In other words, cropping intensification, by reducing the fallow period, boosted the positive effect of N fertilisation on SOC, C fractions and microbial activity. It has been reported that reduced fallow duration improves the overall soil condition (Álvaro-Fuentes et al., 2008; Rosenweig et al., 2018; Gabriel et al., 2021). Therefore, in our experiment, the reduction of the bare fallow period in the PM and BM systems should have improved the overall soil performance. In an irrigated experiment in central Spain, after 10 years, the reduction of the fallow period through the introduction of barley and vetch cover crops between summer maize and sunflower crops improved several soil properties such as reduced penetration resistance and increased SOC and water-stable aggregates (García-González et al., 2018; Gabriel et al., 2021). In that experiment, after two years, SOC and water-stable aggregates in the barley-maize system increased about 29 and 41% compared to the maize monoculture (García-González et al. 2018). In our experiment, the difference between the monoculture and the two intensified cropping systems was lower for SOC (15%) but greater for the water-stable macroaggregates (74%).

It is well established that crop residues and carbon inputs control SOC accrual in agroecosystems (Virto et al., 2012; Fujisaki et al., 2018). In our study, the PM and BM rotations implied two crops per year (pea/barley and maize) whereas in the MM only one crop (maize) was grown per year followed by a 6-month fallow period between the two consecutive maize seasons. Replacing this fallow period with a crop (pea or barley) in the two rotations (PM and BM, respectively) resulted in 15% greater aboveground crop residues which returned to the soil surface. However, according to the results of the correlation analysis, the differences in aboveground crop residues between cropping systems was not enough to explain the variability observed in the soil parameters studied. Therefore, in this irrigated Mediterranean system, other variables such as belowground crop residues or root exudates could be more important drivers of the changes found in the soil parameters studied. It has been observed that root C presents greater mean residence times and, consequently, greater stabilisation in the soil than aboveground crop C (Rasse et al., 2005).

Besides the intensification of the cropping systems, N fertilisation also favours crop residue production and SOC increase (Halvorson et al., 2011; Poffenbarger et al., 2017). However, in an irrigated maize monoculture experiment, also in NE Spain, it was observed that under conventional tillage, N fertilisation did not affect SOC and the related C fractions, but this was positively affected under no-tillage (Pareja-Sánchez et al., 2020). These latter authors concluded that intensive tillage limited crop growth and, in turn, residue production with the concomitant constraint in SOC build-up (Pareja-Sánchez et al., 2020). Furthermore, in our study, also under conventional tillage conditions, in the MM system the crop residues did not respond to N fertilisation. This would explain the lack of response to N fertilisation found in the majority of soil properties in the MM system. However, in the two diversified systems (PM and BM) aboveground crop residues did respond to N fertilisation and, concomitantly, different soil properties were affected by N fertilisation.

Active SOC pool measurements are an effective way of detecting early changes in SOC trends in response to land use and management changes (Cotrufo et al., 2019). In our study, two active C pools were measured, POM-C and POxC. In the two diversified systems, the differences in POM-C between the fertilised and the unfertilised treatments were higher than for POxC and, indeed, significant differences in POM-C were even obtained in PM where no differences were found in POxC. Also, in NE Spain, but under rainfed conditions, it was concluded that POM-C was a better predictor of total SOC changes than POxC for a number of management practices and soil depths (Plaza-Bonilla et al., 2014). This is related to the nature of each active C fraction since the POxC pool is associated with smaller and heavier POM-C and therefore with a higher degree of stabilisation (Culman et al., 2012).

ß-glucosidase has been recognised as an interesting indicator of short-term soil quality changes (Ndiaye et al., 2009) and the stability of this enzyme activity between seasons is also an advantage as a soil quality indicator (Knight & Dick 2004). In our experiment, the ß-glucosidase activity was the only soil parameter which showed differences at both soil depths and it was also the only parameter that positively correlated with aboveground crop residues, showing its ability as a fast-response parameter to reflect changes in soil and crop management.

Conclusions

Our results demonstrate that under Mediterranean irrigated maize conditions, N fertilisation has a positive effect on a number of soil parameters related to soil quality in the short-term. Furthermore, this positive effect of N fertilisation on soil quality may vary depending on the cropping system considered. Indeed, when intensified cropping systems are implemented, N fertilisation increases its positive effect on soil properties related to soil quality. In this sense, in Mediterranean irrigated maize systems the combination of N fertilisation and cropping intensification is a promising strategy for attaining beneficial soil quality effects only two years after the start of the experiment.

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