Grazed temporary grass-clover leys in crop rotations can have a positive impact on soil quality under both conventional and organic agricultural systems

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Grazed temporary grass-clover leys in crop rotations can have a positive impact on soil quality under both conventional and organic agricultural systems

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Abstract

Soil quality (SQ) is the ability of soil to provide ecosystem functions and services. Implementation of a certain agricultural system can affect SQ and therefore play an essential role in achieving sustainable agriculture. The aim of this study was to explore how agricultural systems (conventional vs. organic), grazing regime (non-grazed vs. grazed) and the different proportions of temporary grass-clover leys in crop rotations (ley time proportion, LTP) affect SQ within a mixed (cropping and pasture/dairy system) commercial farming enterprise in the UK. Seven SQ indicators were evaluated, including chemical (pH; available phosphorus (P); potassium (K)), physical (bulk density, BD; aggregate stability, AS) and biological (total carbon (C); microbial biomass carbon, MBC) sectors. All SQ indicators were measured at three depth intervals (0–0.15, 0.15–0.30, 0.30–0.60 m), except for AS and MBC, which were only considered for the topsoil (0–0.15 m). The findings reflected existing knowledge on the advantages of organic vs. conventional systems for SQ indicators, with the former showing higher MBC and similar K, BD, AS and C in the 0–0.30-m compared to the latter. Lower topsoil available P in organic systems can be related to the lack of measurements in all P pools. When grazing was included: (a) both agricultural systems showed higher topsoil available P, C and MBC; and (b) there was a higher topsoil K in organic systems, whereas it positively affected topsoil BD and C (0.15–0.30 m) in conventional systems. Increasing LTP to 30–40% of the full crop rotation increased topsoil AS and C (0–0.30 m) in a linear fashion. Subsoil conditions (>0.30 m) favoured K, BD and C in conventional systems, but these results should be considered carefully. It was concluded that both organic and conventional systems delivered similar levels of SQ and that reviving mixed farming systems may be a key factor for delivering multifunctional agroecosystems that maintain SQ and optimize ecosystem services.

Highlights

- Single-farm comparison of top- and subsoil quality in organic and non-organic systems.
- The organic system increased microbial biomass carbon but decreased topsoil available phosphorus.
- Grazing increased topsoil available phosphorus, carbon concentration and microbial biomass carbon.
- Temporary leys in rotations increased topsoil aggregate stability and carbon concentration.
- Mixed farming is a key factor for delivering multifunctional agroecosystems.

KEYWORDS

ecosystem services, land management, ley-arable rotation, mixed farming, soil functions, soil health

1 | INTRODUCTION

Although intensification of agricultural activity in the last century has supported rapid growth in the global population, it has also contributed to significant environmental impacts. Soil quality (SQ) and thus sustainable agricultural management of soils has become of global interest due to the soil's critical role in providing ecosystem functions and services (Bünemann et al., 2018; Doran, 2002; Karlen et al., 1997). However, there are uncertainties as to how changes in agricultural systems (e.g., from conventional to organic) and the implementation of mixed farming systems (i.e., arable/livestock), with temporary grass-clover leys in crop rotations, affect the SQ of agroecosystems and consequently the environment.

Discussions on SQ emerged in the 1970s and gained ground when concerns around sustainable agriculture in the mid-1980s attracted public attention. In short, SQ encompasses the capacity of the soil to deliver key functions within a particular ecosystem/land use and to sustain biological productivity whilst maintaining or even improving water and air quality and human, plant and animal health (Bünemann et al., 2018; Doran, 2002; Karlen et al., 1997). Based on this definition, it is impossible to directly measure SQ due to its complexity, but it is possible to pursue SQ to ensure sustainability in any given ecosystem. The SQ status of a given ecosystem takes into account inherent and anthropogenic synergies, with the former related to the process of soil-forming and the latter attributed to land use and agricultural management (Karlen et al., 1997; Karlen, Andrews, Wienhold, & Zobeck, 2008). Soil indicators are measured soil properties that are sensitive to anthropogenic activities and linked to soil functions and ecosystem services. Therefore, they are normally used to indirectly assess SQ (Andrews, karlen, & Cambardella, 2004). The selection of soil quality indicators is crucial, and they should be sufficiently diverse to represent chemical, physical and biological soil properties; the most studied ones are total soil carbon (C), pH, phosphorus (P), water storage and bulk density (BD) (Bünemann et al., 2018).

The organic system has been proposed as an attractive agricultural management option to enhance SQ, particularly when compared to non-organic "conventional" systems (Reganold & Wachter, 2016). Organic systems rely mainly on ecological processes, which strive to support as well as enhance biodiversity and biological cycles, thereby re-establishing ecological harmony (IFOAM, 2012). National organic guidelines include practices that may improve SQ, such as diverse crop rotations, mixed farming systems with high animal welfare standards and genetically diverse animal and plant communities, and limited use of all synthetic input sources. This has been confirmed by studies that have shown positive effects on several soil indicators normally used to assess SQ, such as soil C, soil structure and soil microbial biomass (Cooper et al., 2018; Gattinger et al., 2012; Loaiza Puerta, Pujol Pereira, Wittwer, van der Heijden, & Six, 2018; Lori, Symnaczik, Mäder, De Deyn, & Gattinger, 2017; Maeder et al., 2002). Other studies have also indicated that when it comes to environmental aspects, organic systems deliver more benefits than conventional systems (Meier et al., 2015; Mondelaers, Aertsens, & Van Huylenbroeck, 2009; Seufert & Ramankutty, 2017; Tuomisto, Hodge, Riordan, & Macdonald, 2012). However, organic systems could potentially negatively affect some aspects of SQ, which has led to critics claiming that organic systems will be incapable of feeding the projected global population (Connor, 2008; Pickett, 2013). One of the main concerns is that essential nutrients, such as P and potassium (K), may become deficient under long-term organic systems due to restrictions on sources of imported crop nutrients (Möller et al., 2018). On the other hand, conventional systems are recognized as having negative impacts on the environment, including contributing to greenhouse gas (GHG) emissions (Reay et al., 2012; Stavi & Lal, 2012), decreasing biodiversity (Gomiero, Pimentel, & Paoletti, 2011; Tsiafouli et al., 2015), increasing pollution of land and water bodies and degrading soil C (Amundson et al., 2015; Godfray et al., 2010; Lal, 2004, 2007), all of which can be linked to declines in SQ.

It has been recognized that no single approach will solve the challenge of achieving future food security (Reganold & Wachter, 2016). Rather, it may be necessary to adopt some farming practices in combination with other strategies. The inclusion of temporary grass-clover leys in crop rotations (a practice usually implemented in organic systems but also currently encouraged under conventional systems) could help to enhance SQ by regulating the quality and quantity of soil organic matter (SOM) entering the soil system (Paustian, Collins, & Paul, 1997). The use of temporary grass-clover leys in crop rotations has also been suggested to improve soil biodiversity, soil C accumulation and nutrient cycling among many other benefits (Johnston, Poulton, Coleman, Macdonald, & White, 2017; Lori et al., 2017). Recent research has further stressed that if temporary grass-clover leys are grazed (i.e., if the farm is under a mixed arable/livestock system), then there may be an additional benefit to soil C accumulation and enhanced nutrient cycling and utilization, and consequently improved SQ in the agroecosystem (Assmann et al., 2017; Chen et al., 2015).

Despite the potential benefits of mixed farming systems (arable/livestock), there are still uncertainties regarding two key points: (a) the impact of interactive effects between different agricultural systems (conventional vs. organic) and specific practices (e.g., grazing regime: non-grazed vs. grazed) on SQ indicators; and (b) the effect of the length of temporary grass-clover leys (in this study referred to as ley time proportion, LTP) in crop rotations on SQ. To address this current gap in knowledge, this study used a mixed commercial farm (cropping and pasture/dairy system), where conventional and organic agricultural systems co-exist, to evaluate the impacts of agricultural systems, grazing regimes and LTP on SQ. The overarching aims of this study were (a) to evaluate the effects of agricultural systems (conventional vs. organic), grazing regimes (non-grazed vs. grazed) and their interaction on individual SQ indicators, and (b) to assess the effects of LTP in rotations on SQ indicators. The null hypotheses are ultimately that the adoption of the organic system, grazed regime and increases in the LTP do not lead to improvements in any SQ indicators.

2 | MATERIALS AND METHODS

2.1 | Study fields selection and description

The study was performed at Nafferton Farm, a mixed (cropping and pasture/dairy system) commercial farm located in north-east England (54° 59′ 09″ N; 1° 43′ 56″ W, 60 m a.s.l) where both conventional and organic agricultural systems co-exist in a split farm comparison. According to the Köppen classification, the site experiences a marine west coast climatic condition. From 1981 to 2018, the average annual temperature and total precipitation were 8.6°C and 638.6 mm, respectively (Figure S1), with a maximum monthly temperature of 22°C and a minimum of 0°C. The soil is classified predominantly as a Dystric Stagnosol (WRB, 2015): slowly permeable, seasonally wet, acidic loamy to clayey soil that is naturally low in fertility (Cranfield University, 2020; Farewell, Truckell, Keay, & Hallett, 2011). Particle-size distribution analysis indicated that the soil samples used in this study had an average of 14, 45 and 41% of clay, silt and sand, respectively (sandy silt loam), in the top 0.30-m soil layer, and 21, 41 and 38% of clay, silt and sand, respectively (clay loam), in the 0.30–0.60-m soil layer.

Historically, Nafferton farm was a conventional mixed commercial system, with the main activities being a dairy herd, with associated pastoral production, intermixed with a conventional arable cropping system. In 2001, there was a management change from a conventional to an organic system across approximately 50% of the farm area (~160 ha), while maintaining the mixed (dairy and arable) production system on both the conventional and organic parts of the farm. For the past 14 years, the farm has been run with a mixed conventional and a mixed organic agricultural system side by side. Conventional enterprises are operated to current UK best practices (Red Tractor Assurance, 2015) and the organic enterprises to Soil Association (2019) standards. As conventional management was the default system for the preceding 50+ years at Nafferton farm, the comparison between the two agricultural systems (conventional and organic) was made using conventional as the baseline. The study fields were deemed suitable because they had similar soil types and experienced similar climatic conditions.

Twelve commercial-sized representative agricultural fields (~120 ha of the total 320 ha of the farm) were selected for this study (Figure 1). Criteria used when selecting the study fields were recent (2008–2017) agricultural system (S) (conventional (CONV) vs. organic (ORG)), grazing regime (G) (non-grazed-NG vs.

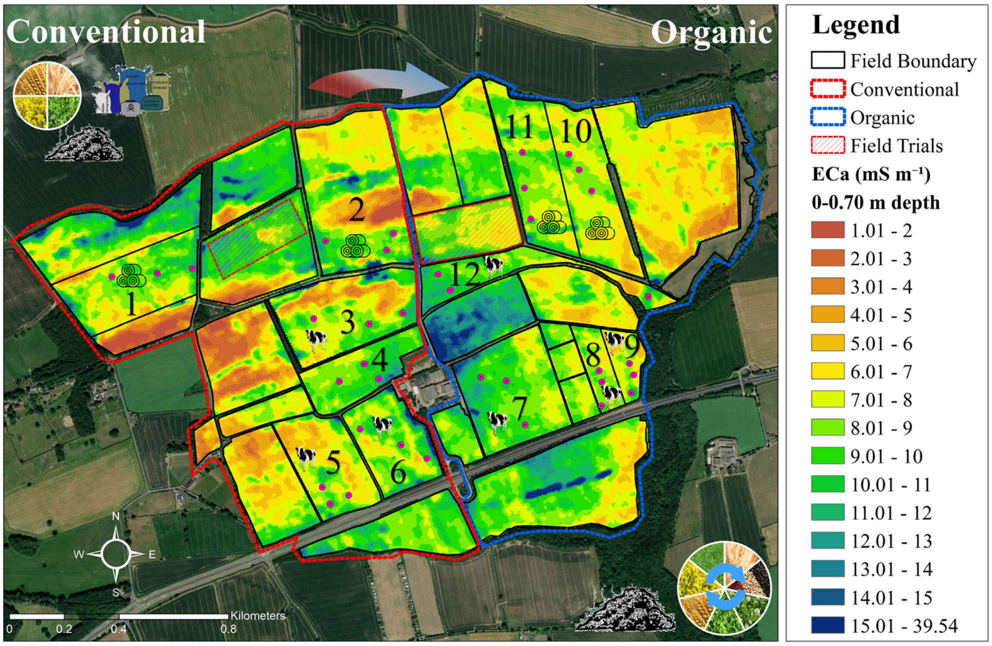

FIGURE 1 Map of spatial variability of apparent soil electrical conductivity (ECa) at 0–0.70-m depth at Nafferton farm, showing the 36 locations (pink points) where the soil cores were taken. Numbers from 1 to 12 refer to the study fields selected across the farm (1–6 conventional and 7–12 organic). Non-grazed and grazed study sites are denoted by hay bales or a cow, respectively [Color figure can be viewed at wileyonlinelibrary.com]

grazed-GG) and crop rotations, that is, the inclusion of temporary grass-clover leys in crop rotations. In general, agricultural systems (conventional vs. organic) were tested using all the 12 study fields, six under a conventional and six under an organic system, which were considered as replicates for each agricultural system. Grazing regime (non-grazed vs. grazed) was tested using four non-grazed and eight grazed study fields (two non-grazed and four grazed study fields within each agricultural system). The stocking rate on the farm is 1–1.5 livestock units ha^{-1}, which was considered to be light to moderate (Soil Association, 2019). Rotations for the organic and conventional agricultural systems did differ slightly, mainly due to the need to have a nitrogen-fixing component within the organic system to support arable production. In addition, ley rotations tended to be longer within the organic system to assist with weed and disease control. As such, it was not possible to have directly paired fields with the same rotational history under the conventional and organic system. Therefore, study fields were deliberately chosen based on the percentage (0 to 100%) of time as temporary grass-clover leys (ley time proportion, LTP) during the previous 10 years and selected within each agricultural system to have a similar spread of LTP (Table 1). In general, the main arable crops grown in the conventional rotation were winter cereals, including winter wheat (*Triticum aestivum*), winter barley (*Hordeum vulgare*) and oilseed rape (*Brassica napus*). Organic rotations included mainly spring wheat and barley and field beans (*Phaseolus vulgaris*). Grass-clover ley periods, in both conventional and organic systems, used a mixture of white and red clover (*Trifolium repens* and *Trifolium pratense*) with perennial ryegrass (*Lolium perenne*). Ley periods in both grazed and non-grazed fields were subjected to two to three harvests for silage per year, depending on their productivity and timing of grazing in the paddock. Further details of management practices in each study field, such as tillage and manure and fertiliser applications, are given in Table 1.

2.2 | Soil sampling methods

The experimental design and the selection of sampling points in each study field were based on *a priori* apparent soil electrical conductivity (EC_a) (0–0.70-m depth) map. This was derived from an on-the-go survey conducted in 2014 using a global navigation satellite systems (GNSS) enabled DualEM-1 s sensor (Milton, ON, Canada) (Figure 1). For consistency and to remove variability between the samples due to textural variation and relative EC_a signal response, three sampling points per field were selected under the following criteria.

- The location had an EC_a value of between 8 and 10 mS m^{-1}.
- The location was at least 50 m away from another within-field sample site.
- It was not located near the field border (> 20 m from a field boundary). It was not located in an area likely to be disproportionately affected by compaction from either machinery or animal activity.

TABLE 1 Details of management practices on the 12 study fields at Nafferton farm over 10 years (2008–2017), indicating agricultural system (conventional and organic), grazing regime (non-grazed and grazed), ley time proportion (LTP) (% years under ley prior to sampling) and manure application proportions (MAP) (% years with manure applied prior to sampling) in the last 10 years, and further details including main crops grown, fertilisation and tillage occurrence that accounted for any activity that turned the soil over for at least 0.15-m soil depth

Study field n° in the map	Agricultural system	Grazing regime	LTP (%)	MAP (%)	Further details
1	Conventional	Non-grazed	0	10	Continuous arable rotation of wheat, barley, and oilseed rape crops for the last 10 years; eight tillage occurrences. Annual fertilisation (mineral and organic forms) of roughly 89, 78 and 156 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
2	Conventional	Non-grazed	10	10	Previously cultivated with ley-arable rotation but became a continuous arable rotation of wheat, barley, and oilseed rape for the last 9 years; five tillage occurrences. Before that, the field had 1 previous year under ley. Annual fertilisation (mineral and organic forms) of roughly 69, 56 and 111 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
3	Conventional	Grazed	70	60	Ley-arable rotation of wheat, barley, and ley; three tillage occurrences. The field is under ley for the last 7 years. Before that, the field had 3 years under wheat, barley rotation. Annual fertilisation (mineral and organic forms) of roughly 148, 46 and 93 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
4	Conventional	Grazed	50	40	Ley-arable rotation of wheat, barley, and ley; four tillage occurrences. The field is under wheat, barley rotation for the last 4 years. Before that, the field had 5 years under ley with 1 previous year under barley. Annual fertilisation (mineral and organic forms) of roughly 89, 31 and 43 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
5	Conventional	Grazed	100	50	Ley-arable rotation field but under ley for the last 10 years; no tillage occurrence. Annual fertilisation (mineral and organic forms) of roughly 130, 28 and 57 kg ha^{-1} yr^{-1} for N, P and K, respectively.
6	Conventional	Grazed	60	40	Ley-arable rotation of wheat, barley,and ley; three tillage occurrences. The field is under ley for the last 4 years. Before that the field had 3 years under arable rotation with 3 previous years under ley. Annual fertilisation (mineral and organic forms) of roughly 190, 79 and 140 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
7	Organic	Grazed	80	60	Ley-arable rotation of wheat, barley,and ley; two tillage occurrences. The field is under ley for the last 7 years. Before that, the field had 2 years under arable rotation with 1 previous year under ley. Annual fertilisation (only organic forms) of roughly 48, 52 and 141 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
8	Organic	Grazed	60	70	Ley-arable rotation of wheat, barley, beans, and ley; four tillage occurrences. The field is under ley for the last 4 years. Before that, the field had 3 years under arable rotation with 2 previous years under ley and 1 year under beans. Annual fertilisation (only organic forms) of roughly 59, 61 and 150 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
9	Organic	Grazed	60	20	Ley-arable rotation of barley, beans, potatoes, and ley; three tillage occurrences. The field is under ley for the last 3 years. Before that, ley was introduced every 2 years of arable crop. Annual fertilisation (only organic forms) of roughly 59, 65 and 170 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.

(Continues)

TABLE 1 (Continued)

Study field n° in the map	Agricultural system	Grazing regime	LTP (%)	MAP (%)	Further details
10	Organic	Non-grazed	30	70	Ley-arable rotation of wheat, barley, beans, and ley; seven tillage occurrences. The field is under arable rotation for the last 5 years. Before that, the field had 3 years under ley with 2 previous years under arable rotation. Annual fertilisation (only organic forms) of roughly 67, 74 and 200 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
11	Organic	Non-grazed	30	60	Ley-arable rotation of wheat, barley, beans and ley; five tillage occurrences. The field is under arable rotation for the last 6 years. Before that, the field had 3 years under ley with 1 previous year under arable. Annual fertilisation (only organic forms) of roughly 71, 79 and 200 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.
12	Organic	Grazed	70	40	Ley-arable rotation of wheat, barley, beans, and ley; three tillage occurrences. The field is under ley for the last 6 years. Before that, the field had 3 years under arable crops with 1 previous year under ley. Annual fertilisation (only organic forms) of roughly 65, 46 and 96 kg ha^{-1} $year^{-1}$ for N, P and K, respectively.

Across the 12 selected study fields, there were 36 sampling points (two agricultural systems; six fields per system; three replicates per study field). At each point, two undisturbed soil cores (0–0.90 m depth) were collected using a hydraulic soil sampler (Atlas Copco Ltd, Hemel Hempstead, Hertfordshire, UK) and a metallic tube (1 m length, 0.03 m inner diameter), totalling 72 sampled cores across the farm. The soil cores were manually cut during sampling into 0–0.15, 0.15–0.30 and 0.30–0.60-m depths, resulting in a total of 216 undisturbed soil core sections. In addition, three disturbed samples (0–0.15 m) were also taken using an auger near each of the 36 sample points to provide 108 disturbed soil samples. Soil sampling was conducted in February–March 2017 and the position of each sampled point was georeferenced with an EGNOS-enabled handheld GPS receiver (Garmin eTrex® 30x, Schaffhausen, Switzerland).

2.2.1 | SQ indicators, soil preparation and analyses

The following seven SQ indicators were analysed: chemical–active acidity (pH), Olsen's phosphorus (P) and ammonium nitrate-extractable potassium (K); physical–aggregate stability (AS) and bulk density (BD); and biological soil C concentration (C) and microbial biomass carbon (MBC). These SQ indicators were chosen based on productivity and environmental protection management goals and their influence on critical/supporting soil functions and potential threats. The productivity and environmental protection goals are related to the capacity of the system to enhance or maintain the production quantity, quality and stability, as well as its efficiency in improving or maintaining soil, air and water quality (Andrews et al., 2004).

Each of the 216 fresh undisturbed samples was gently mixed and passed through a 4-mm sieve; large stones were removed and weighed plant remains were discarded. The weight of the sieved, fresh soil was then recorded. A subsample of the sieved soil (5 g) was used for determination of gravimetric water content. BD was calculated using the core method, adjusting for the weight and volume of large stones (Blake & Hartge, 1986). Thereafter, the duplicate core samples taken at the same georeferenced location and same depth interval were merged and sieved through a 2-mm sieve. This resulted in 108 merged samples, which were then air-dried before being used for particle-size distribution (PSD), pH, P, K and C.

PSD was determined by a low angle laser light scattering technique (laser diffraction) using a Malvern Mastersizer 2000 optical bench (Malvern Instruments Ltd., Malvern, Worcestershire, UK) with recirculating wet cell enhancement and a Hydro 2000MU sample introduction unit. Soil available P concentration was measured by Olsen's P method (Olsen & Sommers, 1982), soil available K was analysed by extraction with NH_4NO_3 (Anon, 1986) and measurement of K concentrations using a flame photometer, and pH was

TABLE 2 Effects of agricultural system (S) (conventional (CONV) and organic (ORG)), grazing regime (G) (non-grazed (NG) and grazed (GG)) and their interaction on soil quality indicators: active acidity (pH), Olsen's phosphorus (P), extractable potassium (K), bulk density (BD), aggregate stability (AS), soil C concentration (C) and microbial biomass carbon (MBC) at three soil depth intervals

		Chemical indicators			Physical indicators		Biological indicators	
Depth (m)		pH H_2O	P mg kg^{-1}	Kmg kg-1	BD Mg m^{-3}	AS %	C g kg^{-1}	MBC mg kg^{-1}
0–0.15	CONV	6.22 (0.09)	29.42 (2.99)	183.08 (37.12)	1.09 (0.02)	73.62 (2.84)	27.68 (1.11)	181.56 (18.33)
	ORG	6.36 (0.08)	12.25 (2.54)	226.25 (55.32)	1.08 (0.02)	69.16 (2.70)	25.72 (0.92)	236.52 (16.34)
	NG	6.36 (0.08)	13.97 (3.46)	135.74 (35.44)	1.12 (0.03)	65.31 (3.44)	23.24 (0.59)	170.37 (22.59)
	GG	6.25 (0.08)	24.27 (2.99)	239.13 (45.11)	1.06 (0.02)	74.43 (2.19)	28.43 (0.86)	228.37 (14.58)
	S	LRT = 0.87; p = .35	LRT = 10.5; $\mathbf{p < .01}$	LRT = 0.11; p = .92	LRT = 0.06; p = .81	LRT = 0.95; p = .33	LRT = 1.63; p = .20	LRT = 4.23; $\mathbf{p = .04}$
	G	LRT = 0.49; p = .48	LRT = 5.18; $\mathbf{p = .02}$	LRT = 1.95; p = .16	LRT = 1.77; p = .18	LRT = 2.86; p = .09	LRT = 9.10; $\mathbf{p < .01}$	LRT = 4.19; $\mathbf{p = .04}$
	S*G	LRT = 1.44; p = .23	LRT = 0.99; p = .31	LRT = 4.25; $\mathbf{p = .04}$	LRT = 5.66; $\mathbf{p = .02}$	LRT = 0.02; p = .88	LRT = 1.38; p = .24	LRT = 0.57; p = .45
0.15–0.30	CONV	6.59 (0.12)	8.72 (0.50)	83.94 (8.03)	1.21 (0.07)	—	20.22 (1.21)	—
	ORG	6.66 (0.10)	9.61 (0.99)	88.44 (15.02)	1.19 (0.07)	—	19.67 (0.59)	—
	NG	6.78 (0.09)	11.00 (1.11)	120.00 (16.36)	1.20 (0.02)	—	18.78 (0.84)	—
	GG	6.54 (0.10)	8.25 (0.54)	69.29 (7.75)	1.20 (0.01)	—	20.53 (0.89)	—
	S	LRT = 0.20; p = .65	LRT = 0.21; p = .64	LRT = 0.38; p = .53	LRT = 0.89; p = .34	—	LRT = 0.01 p = .92	—
	G	LRT = 2.17; p = .14	LRT = 3.76; p = .05	LRT = 10.3; $\mathbf{p < .01}$	LRT = 0.00; p = .97	—	LRT = 1.60; p = .23	—
	S*G	LRT = 0.65; p = .42	LRT = 2.72; p = .10	LRT = 0.46; p = .50	LRT = 0.36; p = .55	—	LRT = 4.89; $\mathbf{p = .03}$	—
0.30–0.60	CONV	7.12 (0.09)	1.39 (0.14)	58.33 (2.62)	1.29 (0.01)	—	13.20 (1.17)	—
	ORG	7.09 (0.07)	1.78 (0.17)	49.72 (2.61)	1.24 (0.02)	—	10.18 (0.59)	—
	NG	7.14 (0.12)	1.58 (0.23)	54.83 (1.86)	1.24 (0.02)	—	11.88 (1.29)	—
	GG	7.08 (0.06)	1.58 (0.13)	53.63 (2.82)	1.28 (0.01)	—	11.60 (0.84)	—
	S	LRT = 0.04; p = .83	LRT = 2.99; p = .08	LRT = 5.00; $\mathbf{p = .02}$	LRT = 2.68; p = .10	—	LRT = 6.48; $\mathbf{p = .01}$	—
	G	LRT = 0.17; p = .68	LRT = 0.00; p = 1.00	LRT = 0.10; p = .75	LRT = 1.63; p = .20	—	LRT = 0.01; p = .91	—
	S*G	LRT = 0.70; p = .40	LRT = 2.14; p = .14	LRT = 0.20; p = .65	LRT = 4.04; $\mathbf{p = .04}$	—	LRT = 0.50; p = .47	—

Note: Data are measured mean values (n = 18 for each S, n = 24 for grazed and n = 12 for non-grazed). The standard error of the mean is in parentheses. Significance tests using a likelihood ratio test (LRT) comparing models with or without the parameter of interest. Significant effects (p < .05) are shown in bold.

measured in H_2O (1:2.5 soil:solution). Soil C concentration was determined by dry combustion, post-combustion and a reduction tube in an Elementar Vario Macro Cube analyser (furnace at 960°C in pure oxygen) (Elementar Analysensysteme GmbH, Langenselbold, Hesse, Germany).

All 108 disturbed soil samples were used for AS and MBC measurements. First, the three samples from the same location point were combined and sieved through a 4-mm mesh to make a composite sample. MBC was assessed using the D glucose respiration rate derived from the MicroResp™ rapid microtitre plate method (Campbell, Chapman, Cameron, Davidson, & Potts, 2003). MBC was calculated from the biomass respiration measurements following procedures described in West and Sparling (1986). The remaining portion of each sample was air-dried and sieved through a 2-mm sieve above a 1-mm sieve. The aggregates collected on the 1-mm sieve (1–2 mm diameter) were used to determine soil AS using a wet-sieving procedure, which measured the effective resistance of the soil structure against either mechanical or physicochemical collapsing forces (Bourget & Kemp, 1957).

2.3 | Statistical analyses

Because the study was carried out on a commercial farm with a stratified selection of the sampling points, spatial autocorrelation and heterogeneity were tested by computing the Moran's I index and via a likelihood ratio test (LRT) comparing the null model (an intercept-only model) and the additional, nested model containing a random effect associated with each study field. The latter was confirmed and, therefore, linear mixed-effects models (LME) were fitted to each individual SQ indicator (pH, P, K, BD, AS, C and MBC) to test the effects of agricultural systems (S) (conventional (CONV) vs. organic (ORG)), grazing regime (G) (non-grazed-NG vs. grazed-GG) and their interaction (S*G). The model structure used S and G as fixed effects, whereas the random effect was defined as the study field to account for the heterogeneity of the experimental design. The analyses were conducted separately for each depth interval.

LME models were also used to test the effects of ley time proportion (LTP) (i.e., % years under temporary

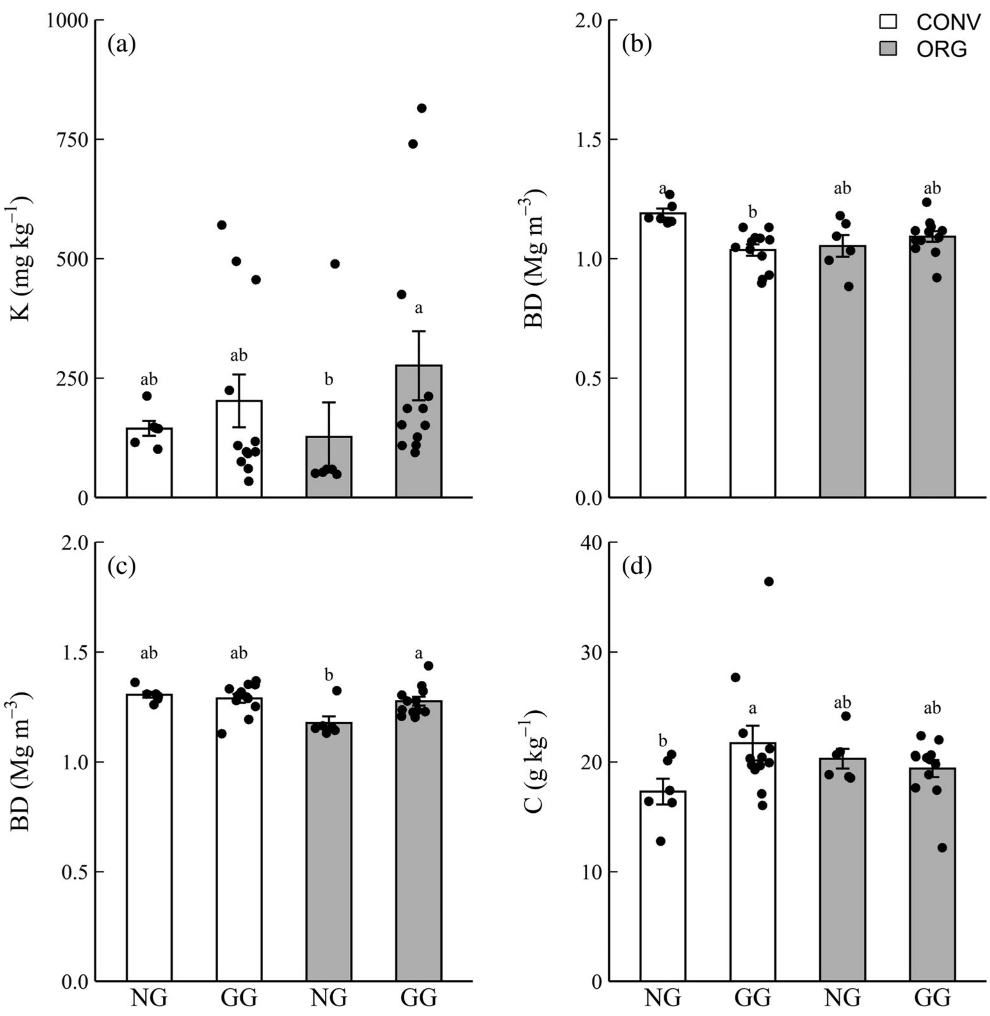

FIGURE 2 Interactive effects between agricultural system (conventional (CONV) and organic (ORG)) and grazing regime (non-grazed (NG) and grazed (GG)) on the following soil quality indicators and soil depth intervals: (a) extractable potassium (K) for 0–0.15 m; (b) bulk density (BD) for 0–0.15 m, (c) bulk density (BD) for 0.30–0.60 m and (d) soil carbon concentration (C) for 0.15–0.30 m. Data are measured mean values ± standard error (SE) (black dots represent individual sample values, $n = 12$ for conventional and organic grazed and $n = 6$ for conventional and organic non-grazed). Significance tests using likelihood ratio test (LRT) comparing models with or without parameter of interest. Mean measured indicator values followed by the same letter do not significantly differ according to Tukey's test ($p < .05$)

grass-clover leys in 10 years) on each individual indicator (pH, P, K, BD, AS, C and MBC). In this case, LTP was used as a continuous variable and as a fixed effect, with study fields as a random effect and analysis being performed separately by depth interval. Although not within the objectives of the study, the same approach was performed to assess potential effects of manure application proportion (MAP) (i.e., % years with manure application in 10 years prior to sampling) on each individual SQ indicator.

For all LME models, assumptions were checked for normality and equal variances by examining the QQ plots of residuals (for both fixed and random effects compartments of the model) and scatterplots of standardized against fitted values. The data were Tukey's Ladder of Powers transformed when visual breakdowns in LME model assumptions were revealed by residual plots. The significance of the fixed effects was determined by comparing models with and without the factor of interest using LRT. When the interaction term in the model was significant, Tukey's HSD post-hoc test was carried out and a significant effect was determined at $p < .05$. All statistical analysis was carried out in the R programming language 3.4.3 (R Development Core Team, 2018) using the additional packages, ape (Paradis, Claude, & Strimmer, 2004), nlme (Pinheiro, Bates, Debroy, Sarkar, & Team, 2018), plyr (Wickham, 2011), ggplot2 (Wickham, 2009) and multcomp (Hothorn, Bretz, & Westfall, 2008).

3 | RESULTS

The data did not show spatial autocorrelation for any of the SQ indicators measured or depth intervals ($p > .05$; data not shown), indicating that the sampling strategy based on EC_a analysis (0–0.70-m depth) (Figure 1) was effective. Agricultural systems (S) (conventional (CONV) vs. organic (ORG)) associated with grazing regimes (G) (non-grazed-NG vs. grazed-GG) and LTP (i.e., % years under temporary grass-clover leys in 10 years) affected soil indicator measurements differently at each depth interval (Table 2 and Figures 2 and 3).

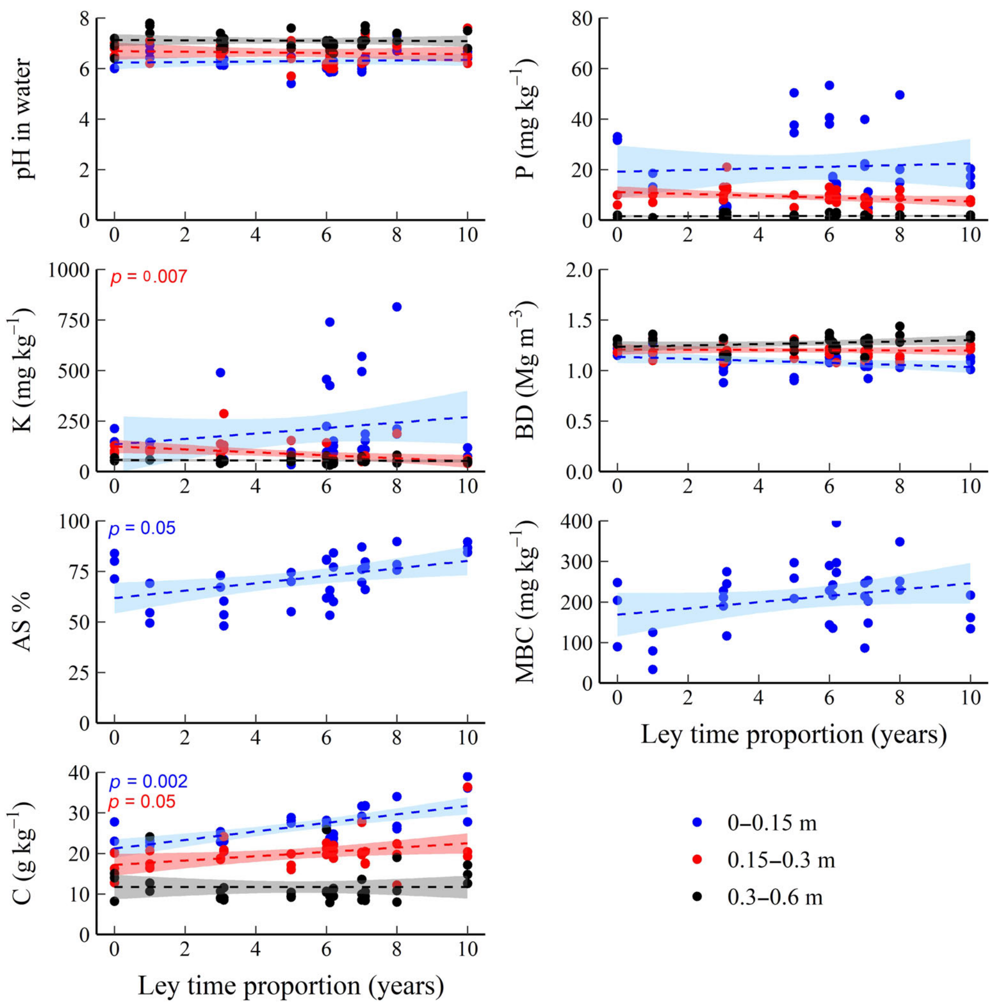

FIGURE 3 Relationship between soil quality indicators: active acidity (pH), Olsen's phosphorus (P), extractable potassium (K), bulk density (BD), aggregate stability (AS), microbial biomass carbon (MBC) and soil carbon concentration (C), and ley time proportion (years). Data are measured indicator values ($n = 36$ for each indicator in each soil depth interval, 0–0.15, 0.15–0.30 and 0.30–0.60 m). Significance tests using a linear mixed effect model (LME). Significant effect ($p < .05$) is shown in the specific soil indicator figure by depth: blue (0–0.15 m), red (0.15–0.30 m) and black (0.30–0.60 m) [Color figure can be viewed at wileyonlinelibrary.com]

In terms of chemical indicators, pH was not affected by S or G at any soil depth interval ($p > .05$). For the 0–0.15-m depth, the ORG system showed lower soil P concentration compared to the CONV system (LRT = 10.53; $p = .001$; Table 2), whereas the GG regime significantly increased soil P concentration under both S (LRT = 5.18; $p = .02$; Table 2). For the 0.15–0.30 and 0.30–0.60-m depth intervals, there was no significant statistical effect of S or G on P concentration (Table 2, $p > .05$). In the topsoil (0–0.15 m), S and G interacted, resulting in an increased soil K concentration with the combination of the ORG system and the GG regime (LRT = 4.25; $p = .04$; Figure 2a), whereas the GG regime had no effect on soil K concentration under the CONV system. Soil K concentration was lower under the GG regimes at 0.15–0.30-m soil depth (LRT = 10.35; $p = .001$; Table 2) and was higher in the CONV system at 0.30–0.60-m soil depth (LRT = 5.00; $p = .02$; Table 2).

For the physical indicators, an interactive effect between S and G was found for soil BD in the 0–0.15 and 0.30–0.60-m layers. The GG regime under the CONV system decreased BD at 0–0.15 m (LRT = 5.66; $p = .02$; Figure 2b), whereas the GG regime under the ORG system increased BD at 0.30–0.60 m (LRT = 4.04; $p = .04$; Figure 2c) relative to NG. The S and G did not affect AS ($p > .05$), even though the GG fields showed approximately 10% higher AS on average relative to the NG fields for the 0–0.15-m depth.

For the biological indicators, soil C concentration was higher under the GG regime in the 0–0.15-m depth (LRT = 9.10; $p = .003$; Table 2). There was an interaction between S and G, indicating that the GG regime increased soil C concentration under the CONV system in the 0.15–0.30-m depth interval (LRT = 4.89; $p = .03$; Figure 2d), but had no effect in the ORG system. The CONV system showed higher soil C concentration in the deeper soil layers (0.30–0.60 m) compared to the ORG system (LRT = 6.48; $p = .01$). The ORG system showed higher soil MBC concentration compared to the CONV system (LRT = 4.23; $p = .04$). The GG regime also significantly increased MBC concentration for the 0–0.15-m depth interval under both S (LRT = 4.19; $p = .04$).

The effects of S (CONV vs. ORG), G (NG vs. GG) and their interactions (S*G) were also assessed on SQ indicators across the whole soil profile (0–0.60 m) (Table S1). Most of the findings reflected those found for the top 0–0.15-m depth interval, except for the soil K and C concentrations, which showed no S or G effects when the whole soil profile was considered. This demonstrates the benefit of individually assessing separate depth intervals as some effects might be masked when soil layers are combined.

Increased LTP did not affect soil pH, P, BD and MBC at any depth interval studied ($p > .05$; Figure 3). There was a trend towards increased topsoil K and MBC concentration (0–0.15 m) as LTP increased. An increased LTP significantly increased AS in the 0–0.15-m depth ($p = .05$) and soil C concentration in the 0–0.15-m and 0.15–0.30-m depths ($p = .002$, $p = .05$, respectively). In contrast, as LTP increased, soil K concentration decreased in the 0.15–0.30-m depth ($p = .007$; Figure 3). MAP (i.e., % years with manure application in 10 years) did not affect any of the soil indicators measured (pH, P, K, BD, AS, C and MBC) at any of the three depth intervals (0–0.15, 0.15–0.30 and 0.30–0.60 m) assessed (data not shown).

4 | DISCUSSION

4.1 | Effects of an organic system on SQ indicators

The lower soil available P concentration in the topsoil (0–0.15 m) in the organic system reflected other studies that have reported challenges with maintaining topsoil available P in organic cropping systems (Cooper et al., 2018; Goulding, Stockdale, & Watson, 2009; Løes & Ebbesvik, 2017). Løes & Ebbesvik, (2017) reported that topsoil available P concentration (0–0.20 m) can decrease by half after conversion from a conventional to an organic system. Cooper et al. (2018), in a recent survey across Europe, found a declining trend in the soil available P concentrations under organic systems. The decrease in soil available P in organic systems is often associated with an imbalance between the export of P in products and the import of nutrients in livestock feed or approved fertilisers. This imbalance can jeopardize the nutient cycling function and reduce the capacity of the organic systems to deliver ecosystem services, such as biomass production, in the long-term (Cooper et al., 2018; Goulding et al., 2009). However, it is also possible that the Olsen's P test does not accurately assess the pool of available P in the organically managed soils (Cooper et al., 2018; Kratz, Schick, & Øgaard, 2016). The broad range of elements provided by organic amendments might have caused sorption of P or immobilization in microbial biomass; these forms of P may be slowly available to crops but not reflected in the results of the Olsen's P test (Möller et al., 2018). In addition, the significantly higher MBC in the organic system should reflect a higher level of microbial activity with increased capacity to mobilize nutrients from inaccessible pools, including organic P and sorbed P (Maeder et al., 2002).

The absence of a difference between the conventional and organic systems in the topsoil (0–0.30 m) K concentration can be explained by the fact that farm yard manure (FYM), used as a source of K fertiliser in the organic system, is providing an equivalent supply of K to conventional K fertilisers (Fortune et al., 2006). Nonetheless, differences in soil K concentrations deeper in the soil profile (>0.30 m) between conventional and organic systems are rarely examined in the literature. Alfaro, Jarvis, and Gregory (2006) investigated the effects of N application and drainage of K in grasslands and found higher K leaching as N application was increased. This was attributed to the acidification of the topsoil by synthetic N fertilisers and displacement of cations (including K) on the exchange complex, leading to K leaching down the profile. This could be a mechanism to explain the elevated concentration of K in the conventionally managed subsoils (0.30–0.60 m) and the lower values in the topsoil, relative to the organic system. The sustained levels of K in the topsoil in organically managed soils indicate effective nutrient retention, possibly on the cation exchange complex, which may be enhanced by the FYM additions.

The higher MBC under the organic system is in agreement with a recent global meta-analysis conducted by Lori et al. (2017), who observed a positive effect on soil microbial community abundance and activities when fields are managed organically. The authors pointed out that organic amendments and a more diverse rotation, particularly with the inclusion of legumes, increased the abundance of the microbial community. In this study, conventional and organic inputs and to a certain extent rotation system were alike, but only the organic part of the farm had the inclusion of nitrogen-fixing beans, whereas oilseed rape was only cropped in the conventional system. Although the conventional part of the farm also received organic fertiliser application (FYM), it was used together with mineral fertilisation, which might have affected the efficiency and/or community composition of the microbial biomass (García-Palacios et al., 2018). This theory is also confirmed by the results of Maeder et al. (2002), who found enhanced microbial biomass in organically managed soils even when compared to the conventional system that used mineral fertiliser plus FYM.

Previous research has reported that organic systems can also increase topsoil (<0.20 m depth) C concentrations (Gattinger et al., 2012; Marriott & Wander, 2006; Scialabba & Müller-Lindenlauf, 2010), with very limited studies assessing deeper layers (Blanco-Canqui, Francis, & Galusha, 2017). In this study, soil C concentrations in the topsoil layers (i.e., 0–0.15 m and 0.15–0.30 m) were not affected, whereas concentrations were lower under the organic system at the 0.30–0.60-m depth interval. Previous research has attributed higher soil C concentrations in organic systems to higher C inputs (through manure, slurry and/or compost application) (Gattinger et al., 2012; Kirchmann, Kätterer, Bergström, Börjesson, & Bolinder, 2016; Leifeld & Fuhrer, 2010), but in this study, both conventional and organic systems had regular applications of FYM, as well as ley periods in the rotation, which might have limited differences between the two systems in the topsoil layers. Moreover, it is worth noting that changes in soil C occur slowly (Smith et al., 2020), and therefore the short period since conversion to the organic system (~ 15 years) may have not allowed for detectable changes.

The significantly higher soil C concentration at 0.30–0.60-m depth under the conventional system contradicted previous work. Blanco-Canqui et al. (2017), in a long-term experiment (+20 years), did not find significant differences in soil C concentrations between a conventional and an organic system below 0.15-m depth, but they highlighted that in the organic system there was a trend towards higher soil C concentrations with the implementation of a more diversified rotation treatment and deep-rooting crops. However, studies comparing soil properties in deeper soil profiles between organic and non-organic systems are limited. In this study, the typically large aboveground biomass in the conventional system should equate to a larger belowground biomass (Bilsborrow et al., 2013). This could have resulted in a larger, deeper rooting system under the conventionally managed soils that enhanced soil C concentrations in the deeper (0.30–0.60 m) layer. This finding has implications for the climate regulation function of soils. Although organic systems are commonly reported to have less of an impact on climate due to lower emissions from fertiliser application (Smith, Kirk, Jones, & Williams, 2019), increasing C concentrations in deeper soil layers could result in increased C sequestration at depth, which may partially offset GHG emissions from conventional systems (Tautges et al., 2019).

Organic systems have been reported to trigger beneficial feedback loops between plants and microbial biomass that ultimately stimulate the plant to promote its own microbial population to increase nutrient availability and utilization from organic material (Hamilton & Frank, 2001; Stockdale, Shepherd, Fortune, & Cuttle, 2006). This is facilitated by microbial exudates, which would also bring further long-term benefits to soil aggregation and to soil C quantity and stability (Loaiza Puerta et al., 2018; Tisdall & Oades, 1982). In this regard, it was expected that soil physical properties (i.e., BD and AS) would be enhanced in organic systems. Where soil type is the same, differences in physical properties such as BD and AS are largely driven by soil C contents. In this study, because soil type and soil C contents were similar for both systems, it is not surprising that AS and BD were also not significantly different when comparing the two systems. This suggests that the soil functions linked to soil structure, including regulation of the water cycle and provision of physically stable aggregates, do not differ between conventional and organic systems.

Overall, the potentially higher organic and microbial forms of P, similar topsoil (0–0.30 m) K, BD, AS and C concentrations and the higher MBC under the organic system indicate that agricultural systems receiving only organic amendments and including nitrogen-fixing plants in the rotation can generate analogous SQ with fewer external inputs than conventional systems.

4.2 | Effects of the grazing regime and its interaction with agricultural systems on SQ indicators

The higher topsoil (0–0.15 m) available P, C and MBC under grazed regimes (compared to non-grazed) were likely to be associated with the higher nutrient returns and enhanced nutrient cycling provided by animals, ley periods and residues left in the soil.

Topsoil (0–0.15 m) available P was 40% and 240% higher under conventional and organic grazed regimes, respectively, when compared with non-grazed counterparts (Table 2). According to Nash et al. (2014), up to 85% of the P applied and taken up by plants is returned to the soil via animal dung in a grazed system. Because animals in a grazed regime act as a nutrient cycling agent (Carvalho et al., 2010), it is likely that they modify both the biochemical form of the nutrients and their spatial distribution, and consequently influence local availability in the soil solution. Moreover, grazing can change plant population dynamics and species diversity, resulting in a different plant ecology system compared to a non-grazed regime (Assmann et al., 2017). This increased soil P availability effect can be found even under light grazing intensities (Assmann et al., 2017) and has been observed across varying mixed (crop-livestock) production systems in Europe (Cooper et al., 2018). However, studies directly comparing conventional and organic mixed farming systems in association with non-grazed and grazed regimes, as compared in this study, are rare (Jackson, Isidore, & Cates, 2019). This finding on soil available P merits particular attention for future discussions on sustainable agriculture strategies as mineral P (as rock phosphate) is a finite resource. Increased available P under organic grazed regimes suggests that grazing residues (urine and dung) and organic amendments are complementary strategies (Assmann et al., 2017), which may be beneficial for cropping systems at a lower level of P supply.

The grazed regime also increased topsoil (0–0.15 m) C concentration and MBC under both agricultural systems (Table 2). Previous studies have also found that implementing grazing can increase topsoil C concentration (Abdalla et al., 2018), indicating that the soil C gains may be limited to the surface layers where the root systems dominate (Chen et al., 2015; Medina-Roldán, Arredondo, Huber-Sannwald, Chapa-Vargas, & Olalde-Portugal, 2008). Increased MBC in grazed fields might be related to interlinked mechanisms regarding the effects of grazing on the microbial community, including changes in biomass production and resource allocation, resource inputs into the decomposers and the plant community itself (Bardgett & Wardle, 2003). Together, these suggest that grazing could be driving soil C accumulation and MBC in the top 0–0.15-m depth due to greater deposition of easily available C inputs and nutrients, which indirectly stimulates belowground biomass (e.g., root growth), followed by greater root turnover and exudations (Chen et al., 2015; McSherry & Ritchie, 2013).

Grazing intensity may influence soil C concentration and MBC positively or negatively by changing individual plant species and plant cover as well as processes that fix C during photosynthesis as a function of microclimate (Abdalla et al., 2018; McSherry & Ritchie, 2013). Because in our study grazing intensity was relatively low and climate parameters were similar for all study fields, the residue amount left in the soil by animals and root growth are likely to be the primary causes of the higher C concentration and MBC in the grazed regimes. We hypothesize that animal trampling may have incorporated part of the residues deposited on the soil surface into the topsoil, whilst also stimulating greater root growth and turnover. These mechanisms could be especially important for the 0.15–0.30-m depth in the conventional system, which showed the lowest soil C concentration in non-grazed fields but a significant increase in grazed regimes (Table 2 and Figure 2). Lower soil C concentration in conventional non-grazed study fields may also be related to the use of more mineral N fertiliser and an increase in residue decomposability (García-Palacios et al., 2018). Although grazed regimes have increased topsoil (0–0.15 m) C concentration and MBC, grazing ruminants on leys results in GHG emissions and reduces land available for cereal crop production. This illustrates the complexity of decision making about land-management practices once the multiple ecosystem services provided by agricultural landscapes are considered. Further research is required to assess the trade-offs between the C sequestration benefits of grazed leys and the wider impacts on the food system.

The grazed regime also interacted with the agricultural system in enhancing topsoil (0–0.15 m) K concentration under the organic system (Table 2 and Figure 2). Grazed organic systems experience a high degree of recycling of K through the return of dung, especially urine, because only a small portion of K is retained in animal products (e.g., milk and meat) (Assmann et al., 2017; Haynes & Williams, 1993). This cycling of K, in combination with higher rates of FYM inputs on organic fields (averages of 100 and 166 kg K ha^{-1} $year^{-1}$, for the conventional and organic system in the last 10 years, respectively) could result in high levels of available K in grazed organic fields.

In contrast, the non-grazed regime showed nearly twice as much available K in the 0.15–0.30 m compared to the grazed fields, regardless of the agricultural system. This corresponds to results from a review conducted in Brazil by de Faccio Carvalho et al. (2010), who found that non-grazed fields have higher K concentrations in the soil profile, in particular from 0.10 to 0.30-m soil depth. The main hypothesis for the higher K concentration in the non-grazed field at depth is that grazed fields possess a denser root system in the topsoil that mines subsurface K reserves (0.15–0.30 m) and recycles and deposits this K onto the soil surface (0–0.15 m). However, more research on the morphology of ley root systems under non-grazed and grazed regimes is required to further elucidate these mechanisms.

Changes in root growth quantity and dynamics might also explain the interactive effect found in soil BD. The decrease in topsoil (0–0.15 m) BD in conventional grazed fields, compared to conventional non-grazed fields, may be linked to the stimulation of root growth resulting in an increase in the root exudation and microbial activities (confirmed by our MBC results and also by Hamilton & Frank, 2001). In organic systems, the higher nutrient availability in the surface layers under grazed fields (Table 2) may have discouraged the need for root development into the deeper soil layers, resulting in a higher BD for 0.30–0.60-m depth. A potential stimulation of surface belowground biomass production by grazing is an important feature as it can amplify the formation of soil aggregates and reduce soil compaction (Dominy & Haynes, 2002). Although not significant ($p = .09$, Table 2), soil aggregate stability was 10% higher in the topsoil of grazed fields compared to non-grazed fields and appeared to be linked to the length of time that a field was in the ley phase (see Section 4.3). This indicates that important soil functions, including mitigation of GHG emissions (Ball, 2013), resistance to soil erosion (Barthès & Roose, 2002) and improved water infiltration and retention, may all be enhanced by grazed ley periods. Our results, therefore, indicate an enhanced SQ from mixed farming systems that could have potential policy implications for the design of multifunctional landscapes.

4.3 | Effects of ley time proportion (LTP) on SQ indicators

Increasing LTP in the crop rotation increased AS (0–0.15 m) and C concentration (0–0.15 and 0.15–0.30 m) under both agricultural systems, whereas it decreased K concentration in the 0.15–0.30-m depth (Figure 3). The decreased soil K concentration at this intermediate-depth interval with increased LTP, supports the notion that a more extensive root system might be mining K from the 0.15–0.30-m depth and depositing it onto the soil surface (0–0.15 m); the trend (non-significant) towards increased topsoil K (0–0.15 m) as LTP increased further supports this hypothesis. The development of a dense root system may also lead to improved soil aggregate stability (i.e., soil structure) and favour the protection and stabilization of SOM as well as associated nutrients (Six et al., 2002). This is supported by the observed increased AS (0–0.15 m) and soil C concentration (0–0.15 and 0.15–0.30 m) with increased LTP.

The results of this study agree with findings from other studies assessing the effects of LTP on soil structure and soil C concentration (Crème et al., 2018; Jarvis et al., 2017; Loaiza Puerta et al., 2018). Jarvis et al. (2017) compared varying proportions of ley (1, 2, 3 or 5 years) in a long-term field trial (60 years) and found that higher proportions of ley time in a rotation improved both topsoil structure and C concentration. Similarly, Loaiza Puerta et al. (2018) reported improved soil aggregate stability and soil C concentration after 2 years following 4 years of arable cropping. Crème et al. (2018) assessed the legacy effect of 3 and 6 years of grassland ley periods after 3 years arable cropping and found that even under short periods (i.e., 3 years) the soil C concentration increased with the implementation of ley periods compared to continuous arable production.

Most previous studies have indicated higher soil aggregate stability and C concentration in a ley–arable rotation compared to continuous arable in the topsoil layers (max. 0.20 m soil depth). This study supports these findings, but also reported increased soil C concentration for intermediate soil layers (i.e., 0.15–0.30 m), which is a significant outcome. In one of the few studies assessing the effects of ley–arable rotations on soil C below 0.20 m, Blanco-Canqui et al. (2017) found no significant effect below 0.15-m soil depth. The authors considered 2-year ley periods in a 4-year crop rotation, concluding that the time under ley (i.e., 2 years) was insufficient to develop an extensive and deep root system to build soil C concentration in the subsoil. Our results suggest that grass-clover ley for approximately 30–40% of the crop rotation (i.e., 3–4 years in a 10-year period) may be required to increase C concentration at 0.15–0.30-m depth. This is particularly relevant for future policies relating to climate change mitigation because building soil C in deeper layers can result in slower rates of decomposition and improve C protection and sequestration in the soil (Lorenz & Lal, 2005). Increasing LTP has increased AS (0–0.15 m) and C concentration (0–0.15 and 0.15–0.30 m) and its wide adoption to improve SQ could result in a return to mixed farming systems and less specialization of crop or livestock farms. This could have GHG implications if total ruminant numbers increased, something that would need investigation using a life-cycle assessment approach to point out the real benefits and/or drawbacks of different scenarios.

5 | CONCLUSIONS

This research was performed in commercial mixed farm in northern England to investigate the impacts of organic and non-organic (conventional) agricultural systems on soil quality (SQ) indicators in both the topsoil and subsoil. More specifically, it investigated how changes from a conventional to an organic system and the presence (or absence) of grazing regimes (non-grazed vs. grazed) and pasture leys in rotation, and their interactions, influenced chemical, physical and biological soil quality indicators. For the topsoil, the findings reflected existing knowledge on the advantages of organic versus conventional systems for SQ indicators. When grazing was included, both agricultural systems benefited from a greatly enhanced SQ, in particular the grazed conventional system. The grazed organic system had a much smaller benefit compared to the non-grazed organic system. The length of pasture leys in the rotation was positively related to SQ regardless of the type of agricultural system, and a grass-clover ley period length equivalent to 30–40% of the full crop rotation is needed to increase AS and soil C concentration in a linear fashion. Subsoil conditions (below 0.30 m) showed a different pattern for SQ to the topsoil. Bulk density and soil C accumulation were favoured under the conventional system, which is hypothesized to be due to a larger and deeper rooting system. Studies into subsoil SQ indicators are less common and the results here show that the agricultural system effects are probably more complex than in the topsoil. However, including grazing and pasture leys in management systems has positive benefits throughout the profile for SQ indicators regardless of whether the system is conventionally or organically managed. Ultimately, reviving mixed farming systems may be a key factor in delivering multifunctional agroecosystems that maintain SQ and optimize ecosystem services, including nutrient recycling/release and utilization. This still needs more research, particularly in furthering knowledge on how subsoil SQ indicators respond to management and also on economic considerations of any proposed changes in management.

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CONFLICTS OF INTEREST

The authors of this study declare no conflicts of interest.

DATA AVAILABILITY

The data that support the findings of this study are available in both the main body of the paper and in Appendix S1 of this article. Raw data can also be provided on request from the corresponding author..

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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