Agron. Sustain. Dev.
DOI 10.1007/s13593-015-0299-9

RESEARCH ARTICLE

No adverse effect of moderate stubble grazing on soil quality and organic carbon pool in dryland wheat agro-ecosystems

Ilan Stavi · Daniel Barkai · Kandikar R. Islam · Eli Zaady

Accepted: 26 February 2015

Abstract Stubble grazing by livestock in post-harvest wheat fields is a common practice. Current knowledge usually shows that grazing has negative effects on soil quality. Therefore, here, we studied the stubble grazing impact on soil quality and crop yields of continuous wheat croplands in the semi-arid northern Negev of Israel. These croplands have experienced the same stubble residue management, meaning, moderate grazing or entire retention, for 18 consecutive years. Cropland soils were also compared with soils of natural lands. Vegetation and 0–10 cm depth soils were sampled in 2013. Results reveal that overall soil quality was generally similar between the two wheat treatments. Moreover, results show that soil under stubble grazing treatment has greater carbon pool index and carbon management index than soil under stubble retention treatment. These findings suggest that the disturbance of soil organic carbon pool is smaller for stubble grazing, contrary to current knowledge. We propose a conceptual model to explain such findings.

Keywords Carbon management-related indices · Agro-pastoralism · Carbon sequestration · Conservation agriculture · Crop residue mulch · Ecosystem services · Mixed farming systems · Readily oxidizable (labile) carbon · Sheep and goat grazing · *Triticum aestivum* L

1 Introduction

Wheat (*Triticum aestivum* L.) grown under rain-fed conditions is a common practice throughout the Middle Eastern drylands. The increase in awareness of conservation agriculture has led to modifications in management practices by using reduced tillage or no-till and crop residue management. Yet, extensive dryland farming systems have still been conventionally managed, resulting in the accelerated degradation of soil quality and reduced crop yields. A substantial decrease in precipitation throughout the eastern Mediterranean since the 1990s has further exacerbated risks to rain-fed wheat production across the region.

Due to its capacity to decrease land degradation rates and severity, conservation agriculture has gained increasing attention around the world (Branca et al. 2013; Kirkegaard et al. 2014). Among the relevant management practices, the on-site retention of crop residue is one of the most important (Bell et al. 2011). The effect of crop residue clearing from the ground surface has been widely reported to decrease pools of soil organic carbon (Wang et al. 2005; Du et al. 2014), and increase vulnerability to raindrop impact, resulting in the formation of mechanical crusts (Paul et al. 2013), and diminished water infiltrability and soil moisture content (Govaerts et al. 2007). Tillage action has been reported in many studies to cause deformation of the soil structure, and to exacerbate oxidation of soil organic carbon (Stavi and Lal 2013). This further decreases stability of the soil structure, diminishing the soil hydraulic conductivity, and increasing water runoff and soil erosion. The combined effect of crop residue clearing and

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I. Stavi (✉)
Dead Sea & Arava Science Center, 88840 Ketura, Israel
e-mail: istavi@adssc.org

I. Stavi
e-mail: istavi@yahoo.com

D. Barkai · E. Zaady
Department of Natural Resources, Agricultural Research Organization, Gilat Research Center, 85280 Negev, Israel

K. R. Islam
Ohio State University South Centers, Piketon, OH 45661, USA

soil tillage has been reported to cause degradation of the soil structure and depletion of soil organic carbon, consequently decreasing the fertility and the productive capacity of the agro-ecosystem (Stavi and Argaman 2014), and causing the emission of substantial amounts of carbon dioxide to the atmosphere (Stavi and Lal 2013). In addition to crop residue clearing, the trampling action by livestock under unsustainable regimes of stubble grazing may cause soil compaction and ground surface shearing, further increasing susceptibility to deformation of the soil structure and to accelerated wind and water erosion (Radford et al. 2008). Over time, the loss of the fertile uppermost layers of the soil could result in loss of crop yields, decreased economic incomes, and diminished provision of ecosystem services (Stavi and Argaman 2014).

In the semi-arid region of Israel, the extent of rain-fed wheat has encompassed approximately 50,000 ha (Afic Environmental Engineering and Hydrology 2011). While lands have been regularly managed under intensive plowing, a substantial part of them have been transformed throughout time to conservation farming systems by using no-till or, in practice, occasional tillage. In both types of land management, the wheat straw is collected upon harvest and used for livestock feeding, either as hay or, at the end of the growing season, as straw. In most cases, the remaining 10-cm ground-attached stubble is utilized for livestock grazing. In years when the precipitation regime and quantity are inadequate, the wheat does not justify harvesting for grains in either tilled- and no-till systems. In such years, the entire shoot biomass, including the spikes, is harvested for hay. Regardless, in most years, the revenues generated for farmers by selling hay are considerably smaller than those from grains. Climatic changes throughout the region, of typically lower precipitation rates and higher temperatures, are exacerbating pressures on these agro-ecosystems.

In the Middle Eastern drylands, the on-site, entire retention of crop residues on the ground surface is hardly ever carried out since the demand for fodder for the livestock sector is enormous (Ryan et al. 2008b). Also, in mixed farming systems, moderate stubble grazing can often be considered both pragmatic and strategic in terms of economic risk reduction at the farm level (Kirkegaard et al. 2014). Yet, the retention of the ground-attached, lowermost 10-cm stubble could be considered relevant if proven to be advantageous in terms of soil quality preservation and crop yield increase. Therefore, the objective of this study was to assess the effects of a long-term moderate stubble grazing regime in dryland wheat systems on soil quality and crop yields. This was studied by comparing it to an on-site stubble retention regime, as well as to a reference, “natural” land, which has not been under any agricultural or pastoral use for several decades. The study was implemented in continuous wheat croplands, each of which has experienced the same management practice of stubble residue, meaning, grazing or retention, for 18 consecutive years. The study hypothesis was that compared to the on-site retention of the lowermost 10-cm stubble, the stubble grazing, even if implemented to a moderate degree, increases soil compaction and decreases soil organic carbon pools. Therefore, it was also hypothesized that overall soil quality is greatest under the natural land and lowest under the wheat system with stubble grazing.

2 Materials and methods

2.1 Regional settings

The study was conducted at the Migda Farm (31° 20′ N, 34° 39′ E) of the Israeli Ministry of Agriculture–the Agricultural Research Organization, located in a semi-arid region in the northern Negev desert. The predominant soil type is Loessial Serozems (Haplargids) with sandy loam texture. The mean daily temperature ranges between 12 °C in January and 26 °C in July. Typical inter-annual rainfall regime is 200 mm, occurring between November to March.

In years with cumulatively large amounts of rain of at least 250 mm y^{-1}, which are well distributed throughout the growing season, the grains are harvested in the early summer and the straw is baled. In other years, the entire above-ground biomass is harvested and baled for hay in the early spring, when it is still greenish. Records of cumulative annual precipitation rates recorded by a nearby meteorological station revealed that during a period of 18 years between 1995 and 2013, a total of 15 of the years received precipitations lower than 250 mm. Specifically, this scenario occurred in the 2012–2013 growing season, when annual precipitation was distributed between November and February, had yielded a total of 184 mm, and did not support wheat growth to an extent that justified grain harvest. In extremely dry years, when even harvest for hay is not feasible, livestock is allowed to graze the entire above-ground biomass in mid-summer. These scenarios represent well the prevailing farming practices across the semi-arid Negev region.

The Migda Farm covers an area of ~200 ha of rain-fed land divided into enclosures of 5–10 ha each and has been continuously used for wheat production since the mid 1990s. In late autumn of every year, the farm’s lands are lightly disked to a depth of 5-cm and then wheat is sown by drill at a rate of 90 kg ha^{-1}. Every year, while in some enclosures the post-harvest 10-cm height stubble and straw residue remain intact (Fig. 1), in other enclosures this vegetative material is moderately grazed by flocks of sheep and goats during June to July, after which approximately 0.3 Mg ha^{-1} of dry matter remains as mulch on the ground surface (Fig. 2). In terms of land-use and complementary management practices, none of these enclosures experienced any change between 1995 and 2008. In 2008, all these lands were converted to an organic farming

Fig. 1 Continuous wheat cropping system with stubble retention

system and no agrochemicals have been used for either pest control or fertilizing since. At the same time, no organic additives have been applied for nutrient management as a way of imitating prevailing management practices across extensive lands in the semi-arid northern Negev. Regardless of the applied conventional/organic management system, the same treatment of stubble grazing/retention has remained in each of the enclosures with no change between 1995 and 2013.

A "natural" land area of ~20 ha adjacent to the farm was used as a reference to the wheat treatments. This natural land is comprised of stabilized gullies and wide inter-gully spaces. Dense vegetation consisting of grasses and herbaceous forbs, as well as sparsely distributed woody vegetation cover this land, stabilizing the system against further erosional processes. As a means of land conservation, this natural land area has been left ungrazed and not used for any other purpose for several decades.

2.2 Plots design, on-site monitoring, and sampling of vegetation and soil

Three enclosures, each with an area of approximately 5 ha, were randomly selected as replicated sampling plots within each of the two wheat treatments. On the natural land, three plots of 10×10 m were designated on the upper, flat landform that stretches over the inter-gully spaces, with a distance of at least 200 m between adjacent plots. Fieldwork was conducted in mid-March 2013, 1 week before the wheat harvest for hay. In each enclosure of each wheat treatment and plot of natural land, vegetation and soil were sampled in seven randomly selected spots. Sampling of vegetation was performed by recording the shoot height and harvesting the entire above-ground biomass in a 20×20 cm quadrat. Sampling of soil at the 0–5 and 5–10 cm depths was conducted with cores of 50 mm diameter×50 mm height to obtain undisturbed samples, as well as by obtaining ~500 g of the whole soil. Samples of both the cores and the whole soil were placed in sealed plastic bags to prevent evaporation and kept under cool and shaded conditions until arriving at the laboratory. Additionally, the soil wetness front was determined on-site by pushing a designated probe into the soil (Eldridge et al. 2000) in each of the 20×20 cm quadrats. For all these variables, the total number of samples (*n*) was 126. In April 2013, after the wheat harvest and before introducing livestock to the stubble grazing plots, the remaining above-ground biomass was sampled in five 20×20 cm quadrats per enclosure of each of the wheat treatments (*n* of 30).

Fig. 2 Continuous wheat cropping system with stubble grazing

Complementary field work was performed in mid-August 2013, following stubble grazing in the grazing plots, and when the soil moisture content had reached the hygroscopic level (1.6±0.1 %). This included the on-site measurements of ground surface soil penetration resistance by using a hand cone penetrometer (Eijkelkamp®, the Netherlands), shear strength by using a vane shear tester (Eijkelkamp®, the Netherlands), and unsaturated infiltration capacity for 5 min duration by using a minidisk infiltrometer (Decagon®, USA). This complementary field work was implemented in the same enclosures and plots, and according to the same settings as the March sampling session.

2.3 Laboratory analyses of vegetation and soil

Field-moist samples of entire above-ground biomass and stubble biomass of each of the wheat treatments, as well as of above-ground biomass of herbaceous vegetation for the natural land, were oven-dried at 60 °C for 24 h to calculate for dry weight. Biomass removal rate for the wheat treatments was then calculated using the equation:

$$((\text{total dry above–ground biomass}-\text{dry stubble biomass}) \times 100) / (\text{total dry above–ground biomass})$$

Sub-samples of soil were oven-dried at 105 °C for 24 h to determine gravimetric moisture content. Soil bulk density was determined by the core method (Grossman and Reinsch

2002). Content of calcium carbonate was determined with a calcimeter (Loeppert and Suarez 1996). Total soil organic matter concentration was determined by the loss-on-ignition method (Nelson and Sommers 1996) after fumigation with diluted hydrochloric acid (Harris et al. 2000). The results were then divided by 1.724 to calculate for total soil organic carbon. Labile (readily oxidizable) soil organic carbon concentration was determined by the mild potassium permanganate oxidation method (Weil et al. 2003).

Using the total soil organic carbon and labile organic carbon data enabled the calculation of the carbon lability, as well as the soil organic carbon management-related indices, including the carbon pool index, carbon lability index, and carbon management index (Blair et al. 1995).

The carbon lability was calculated by the equation:

$$\text{Carbon lability} = (\text{labile organic carbon}) / (\text{non-labile organic carbon}) [\%/\%]$$

where the non-labile organic carbon fraction was calculated by subtracting the labile organic carbon from the total soil organic carbon.

The carbon pool index was calculated by the equation:

$$\text{Carbon pool index} = (\text{total soil organic carbon in wheat treatment soil}) / (\text{total soil organic carbon in reference soil})$$

where the soil under the natural land was referred to as the reference.

The carbon lability index was calculated by the equation:

$$\text{Carbon lability index} = (\text{Lability in wheat treatment soil}) / (\text{Lability in reference soil})$$

where again, the soil under the natural land was referred to as the reference.

The carbon management index was calculated by the equation:

$$\text{Carbon management index} = \text{Carbon pool index} \times \text{Carbon lability index}$$

2.4 Statistical analysis

Analysis of variance was conducted with the general linear model procedure of SAS (SAS Institute 1990) to examine the effect of land-use and soil depth on the different soil and vegetation features. Factors used in the model for gravimetric moisture content, bulk density, calcium carbonate content, total soil organic carbon content, labile organic carbon content, and carbon lability were land-use (2 degrees of freedom: df), plot within land-use (6 df; error term for plot), soil depth (1 df), and the interaction land-use×soil depth (2 df). Factors used in the model for the carbon pool index, carbon lability index, and carbon management index were: land-use (1 df), plot within land-use (3 df; error term for plot), soil depth (1 df), and the interaction land-use×soil depth (1 df). When statistically significant interactions were found, they were subjected to additional analysis of variance with the slice command of the general linear model procedure. Land-use (2 df) and plot within land-use (6 df; error term for plot) were the factors in the model for the vegetation variables and for the soil's wetness front, penetration resistance, shear strength, and water infiltration capacity. Separation of means was implemented by Tukey's Honestly Significant Difference (HSD) at a probability level of 0.05. Pearson correlation coefficients were computed to assess the relations between each pair of properties.

3 Results and discussion

3.1 Land-use (change) impact

Compared to natural and undisturbed grasslands or shrublands, croplands usually experience lower soil quality. This effect is mainly attributed to the greater output and smaller input of organic materials, resulting in decreased total soil organic carbon and increased bulk density (Wang et al. 2008). As a result, the infiltration capacity of water and the soil moisture content are usually greater under natural lands than those under croplands (Schwartz et al. 2003). However, our results only partially align with this scenario. On the one hand, compared with the two wheat treatments, the soil under the natural land had significantly smaller bulk density, and significantly greater total soil organic carbon. In addition, the soil under the natural land had a significantly greater labile organic carbon than that under the stubble retention treatment, though only slightly and not significantly greater labile organic carbon than that under the stubble grazing treatment. Also, the shear strength was significantly greater in the soil under the natural land than that under each of the wheat treatments (Table 1). The negative (r of −0.53) and significant (P of 0.0392) correlation between bulk density and shear strength further reveals the greater physical quality of soil under the natural land than that under the wheat treatments, and presumably demonstrates the effect of the root system's biomass and density on these soil characteristics. On the other hand, no differences between the natural land and the two wheat treatments were recorded for either the wetness front or moisture content. In addition, unexpectedly, the soil under the natural land had greater penetration resistance than that under each of the two wheat treatments, though it was significant only in regard to the stubble grazing treatment. Moreover, the significantly smaller infiltration capacity in soil under the natural land than that under each of the wheat treatments (Table 1) was unexpected.

These differences between the natural land and the two wheat treatments could be attributed to the extensive occurrence of biological crusts, observed on the natural land's ground surface. This is in accordance with Eldridge et al. (2000), who revealed that biological crusts in the northern Negev can have a hydrophobic effect, limiting the infiltration capacity of water into the soil. This also concurs with our observations during the 2013 rainy season, revealing the emergence of small puddles from raindrops on the natural land's surface. This hydrophobic effect also explains the significantly greater content of calcium carbonate under the natural land than that under each of the two wheat treatments, presumably caused by the smaller leaching capacity of the soil under the former compared with that under the two wheat treatments. Yet, in this regard, it is noteworthy to mention previously reported controversial observations regarding the effects of biological crusts, with the potential positive or negative effect on soil infiltration capacity (Chamizo et al. 2012). Either way, the greater shear strength of soil under the natural land than that under each of the two wheat treatments (Table 1) is probably also related to the well-developed biological crusts which cover the ground surface of the former. The combined effect of these crusts is demonstrated by the strongly negative (*r* of −0.65) and highly significant (*P* lower than 0.0001) correlation between the soils' unsaturated water infiltration capacity and shear strength.

3.2 Stubble management effect on soil quality

When comparing the two wheat treatments, it was expected that the trampling action in the stubble grazing treatment plots

Table 1 Land-use effect on soil's wetness front (cm), penetration resistance (MPa), vane shear strength (kPa), bulk density (Mg m^{-3}), gravimetric moisture content (%), unsaturated infiltration capacity (cm sec^{-1}), calcium carbonate content (%), total organic carbon content (g kg^{-1}), labile organic carbon content (ppm), carbon lability (%/%), carbon pool index, carbon lability index, carbon management index, above-ground biomass dry weight (Mg ha^{-1}), biomass height (cm), stubble weight (Mg ha^{-1}), biomass removal rate (%), and inter-annual hay yield (Mg ha^{-1})

	P value	Wheat with stubble grazing	Wheat with stubble retention	Natural land
Wetness front	0.3409	67.8 a (2.3)	65.7 a (2.1)	62.9 a (2.4)
Penetration resistance	**0.0402**	0.49 b (0.01)	0.53 ab (0.02)	0.56 a (0.03)
Vane shear strength	**<0.0001**	69.7 b (4.9)	73.6 b (6.4)	181.6 a (9.5)
Bulk density	**<0.0001**	1.66 a (0.03)	1.65 a (0.01)	1.48 b (0.02)
Gravimetric moisture content	0.718	6.6 a (0.3)	6.4 a (0.3)	6.3 a (0.2)
Unsaturated infiltration capacity	**<0.0001**	0.0022 a (0.0001)	0.0016 b (0.0002)	0.0007 c (7.89×10–5)
Calcium carbonate content	**<0.0001**	12.4 b (0.1)	11.3 c (0.1)	14.2 a (0.3)
Total organic carbon content	**<0.0001**	20.3 b (0.3)	17.7 b (0.7)	24.3 a (1.2)
Labile organic carbon content	**0.0067**	9.3 ab (0.4)	8.1 b (0.4)	9.9 a (0.5)
Carbon lability	**<0.0001**	0.0218 b (0.0004)	0.0257 a (0.0011)	0.0197 b (0.0008)
Carbon pool index	**0.0005**	0.84 a (0.01)	0.73 b (0.03)	–
Carbon lability index	**0.0015**	1.11 b (0.02)	1.30 a (0.05)	–
Carbon management index	**0.0491**	0.92 a (0.01)	0.89 b (0.01)	–
Above-ground biomass weight[a]	**0.0228**	2.2 ab (0.2)	3.1 a (0.4)	1.7 b (0.4)
Biomass height[a]	**<0.0001**	55.9 a (2.3)	59.1 a (2.8)	28.1 b (3.6)
Stubble weight[b]	0.3765	0.90 a (0.11)	0.87 a (0.05)	–
Biomass removal rate	0.2653	73.6 a (2.6)	67.2 a (4.9)	–
Inter-annual hay yield[c]	0.8573	1.78 (0.35)	1.69 (0.34)	–

[a] One week before harvest for hay

[b] After wheat harvest and before stubble grazing

[c] Unpublished data, provided by D. Barkai. Means within the same row followed by a different letter differ at the 0.05 probability level according to Tukey's Honestly Significant Difference (HSD). Numbers within parentheses are standard error of the means

Bold *P* value indicate a significant effect would increase the ground surface penetration resistance and augment the soil bulk density (Agostini et al. 2012; Lenssen et al. 2013). Also, the shearing and grinding of the surface soil—imposed by the hoof action—was expected to decrease the ground surface shear resistance. However, soil penetration resistance was slightly—though not significantly—greater under the stubble retention treatment than that under the stubble grazing treatment, and no differences were found between these two treatments for either of the soils' bulk density and shear strength. Moreover, soil under the stubble grazing treatment had significantly greater infiltration capacity. Yet, the wetness front and moisture content were rather similar in the two wheat treatments (Table 1). Regardless, the obtained results suggest that the overall effect of livestock on the physical quality of soil under the moderate stubble grazing regime is not considerable. These results could presumably be related to the dry conditions of soil during the summer, minimizing the adverse effect of livestock trampling on the soil's physical characteristics (Radford et al. 2008). These effects are expected to be different when grazing is imposed in moist soil conditions, where trampling would increase compaction of soil and deformation of soil structure (Bell et al. 2011).

A significantly greater calcium carbonate concentration was observed for the soil under the stubble grazing treatment than that under the stubble retention treatment (Table 1). This contradicts the same trend in infiltration capacity, which presumably suggests greater leaching capacity under the stubble grazing treatment than that under the stubble retention treatment. Yet, to some extent, the stubble grazing treatment effect on calcium carbonate is supported by Stavi et al. (2008) who showed for the northern Negev rangelands that livestock trampling results in an increase in soil concentration of calcium carbonate. In this regard, it is noteworthy to mention that the soil concentration of calcium carbonate is relatively stable and would not be easily modified by short-term management practices (Stavi et al. 2008). Nevertheless, it is expected that the almost two decades during which the study's enclosures have experienced the same grazing treatments would suffice in generating modifications of this soil feature.

3.3 Stubble management effects on crop yields and soil organic carbon dynamics

Soil organic carbon is known to be prone to modifications by agronomic activities, which affect both the quantity and quality of its pools (Weil et al. 2003; Du et al. 2014). The much greater rate of biomass retention on the ground surface under the stubble retention treatment—~0.8 Mg ha^{-1}dry matter—than that under the stubble grazing treatment—~0.3 Mg ha^{-1} dry matter—was expected to generate considerable differences in soil quality and crop yields between these treatments. First and foremost, it was expected to result in a difference in the soil's concentration of total organic carbon (Ryan et al. 2008a; Barsotti et al. 2013) and labile organic carbon. This is due to the anticipated close relationship between the rate of stubble retention and the input of organic residue into the soil matrix (Du et al. 2014). Also, the greater total soil organic carbon is anticipated to improve the soil quality, increasing potential net primary productivity. However, for the pre-grazing vegetation indicators, including dry above-ground biomass and biomass height, as well as for the stubble dry weight and biomass removal rate, the differences between the two wheat treatments were not significant. This aligns with long-term data of hay yields at the Migda Farm, showing a general similarity between the two treatments (Table 1). Also, this is in accordance with Landau et al. (2007), who reported for the same study region that long-term stubble grazing has not significantly decreased yields and quality of wheat grains. These results from the Israeli Negev concur with Bell et al. (2011), who reported no detrimental effect of moderate stubble grazing on crop yields of rain-fed wheat agro-ecosystems in eastern Australia. Regardless, the relatively small yields under both of the wheat treatments—negating the viability of harvests for grains and leading to the less profitable early harvesting for hay—should be of concern.

For each of the total soil organic carbon and labile organic carbon, values were slightly, though not significantly, greater under the stubble grazing treatment than those under the stubble retention treatment (Table 1). This difference for labile organic carbon is in accordance with the perception of greater lability of livestock-derived organic matter excreted in manure, than that of wheat's stubble-derived organic matter (Corsi et al. 2012). Additionally, significant differences were recorded between the two wheat treatments for the carbon lability—which indicates the ratio between labile organic carbon and non-labile organic carbon—that was significantly greater under the stubble retention treatment than that under the stubble grazing treatment. Also, significant differences were recorded between the two wheat treatments for each of the management-related soil organic carbon indices: (1) the carbon pool index – which indicates the effect of land-use change or management practice on aggradation or degradation of the total soil organic carbon—was significantly greater under the stubble grazing treatment than that under the stubble retention treatment; (2) the carbon lability index—which indicates the ratio between carbon lability in the treatment soil and carbon lability in the reference soil—was significantly greater under the stubble retention treatment than that under the stubble grazing treatment; and (3) the carbon management index—which predicts changes in sequestration and lability of soil organic carbon as a result of changes in agricultural practices—was significantly greater under the stubble grazing treatment than that under the stubble retention treatment (Table 1). Blair et al. (1995) demonstrated that overall, the more drastic the land-use change, for example, from natural land to cultivated land, or the more intensive the applied

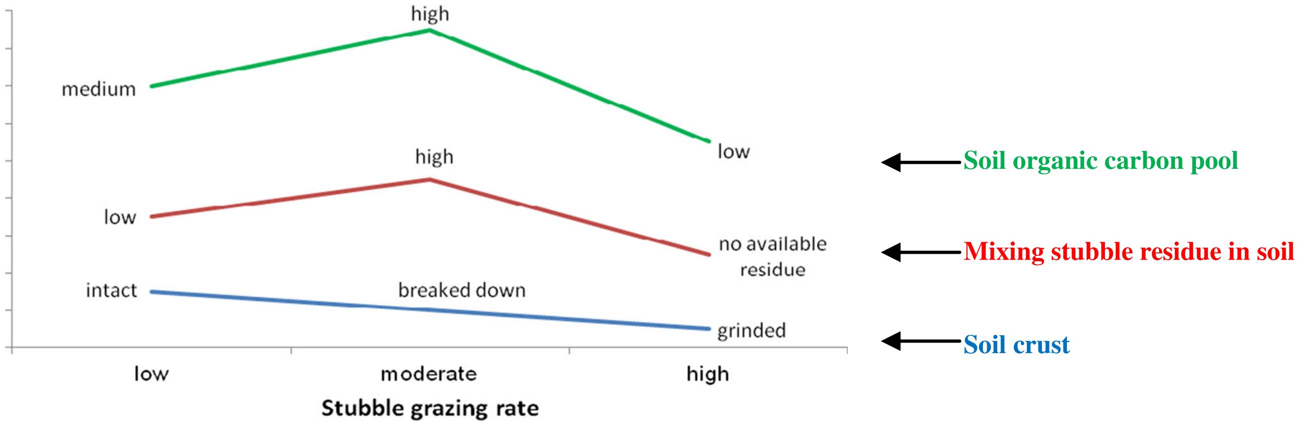

Fig. 3 A conceptual model of the effects of stubble grazing rate on soil crust, mixing stubble residue in the soil, and soil organic carbon pool. According to this, low grazing rate has no effect on the soil crust, negating the mixing of stubble residue in soil, and resulting in medium organic carbon content in soil; medium grazing rate breaks the soil crust, enabling the mixing of stubble residue in soil, and resulting in high organic carbon content in soil; high grazing rate grinds the soil crust and leaves no stubble residue, considerably diminishing the organic carbon content in soil

management practice, the greater the decrease in each of the carbon pool index, carbon lability index, and carbon management index. Therefore, the greater carbon pool index and carbon management index observed for the stubble grazing treatment than those for the stubble retention treatment suggest that the overall disturbance of soil organic carbon pool by the land-use change from natural land to cropland is smaller under the former than that under the latter. However, the smaller carbon lability index under the stubble grazing treatment than that under the stubble retention treatment does not comply with this suggestion.

In terms of novelty, it is proposed that in the long run, moderate stubble grazing does not adversely affect the soil organic carbon pool. We propose a conceptual model, according to which the moderate disturbance of the soil surface by hoof action breaks the thin crust cover and increases the mixing of the coarse stubble residues in the uppermost soil layer. The degradation and incorporation of these residues into the soil organic carbon pool is accelerated, compensating for the loss of a large part of the stubble through consumption by the livestock. At the same time, a high stocking rate would grind the soil surface, clear off the stubble from the system, and deplete the soil organic carbon pool (Fig. 3). This conceptual model is supported by our observations and data obtained for the entire stubble retention treatment versus moderate stubble grazing treatment. At the same time, data regarding a high stocking rate is based on reasonable assumptions. An alternative explanation to the no adverse effect of the moderate stubble grazing treatment could be that the qualitative effect on organic matter input from the livestock feces is of relatively high impact, compensating for the quantitative output of organic matter through stubble consumption. Moreover, mixing

Table 2 Soil depth effect on soil's bulk density (Mg m^{-3}), gravimetric moisture content (%), calcium carbonate content (%), total organic carbon content (g kg^{-1}), labile organic carbon content (ppm), carbon lability (%/%), carbon pool index, carbon lability index, and carbon management index

P value	*P* value	0–5 cm	5–10 cm
Bulk density	***P*=0.0179**	1.57 b (0.03)	1.63 a (0.01)
Gravimetric moisture content	***P*<0.0001**	5.6 b (0.2)	7.2 a (0.1)
Calcium carbonate content	*P*=0.2984	12.6 a (0.2)	12.7 a (0.2)
Total organic carbon content	***P*=0.0022**	22.2 a (0.8)	19.3 b (0.7)
Labile organic carbon content	***P*=0.0069**	9.8 a (0.4)	8.5 b (0.3)
Carbon lability	***P*=0.0158**	0.0212 b (0.0069)	0.0236 a (0.0008)
Carbon pool index	***P*=0.0212**	0.75 b (0.02)	0.82 a (0.02)
Carbon lability index	*P*=0.4697	1.23 a (0.04)	1.18 a (0.05)
Carbon management index	***P*=0.0009**	0.88 b (0.01)	0.93 a (0.01)

Means within a row followed by a different letter differ at the 0.05 probability level according to Tukey's Honestly Significant Difference (HSD). Numbers within parentheses are standard error of the means

Bold *P* value indicate a significant effect the feces—together with the stubble residue—in the uppermost soil layer is expected to further accelerate their incorporation into the soil organic pool. Regardless, the obtained results do not support the study's hypothesis, and require further investigations in order to identify the mechanisms through which the hoof action, the biomass consumption, and the feces excretion affect the soil organic carbon pools and dynamics.

3.4 Soil depth effect

Except for calcium carbonate, the remaining soil characteristics were significantly affected by the soil depth. As expected, these characteristics, including bulk density that was greater at the deeper depth, and both the total soil organic carbon and labile organic carbon that were greater at the shallower depth, revealed greater soil quality at the 0–5 cm depth than that at the 5–10 cm depth. However, the greater gravimetric moisture content in the deeper soil depth was unexpected and did not correspond with the other soil characteristics. Regarding the soil organic carbon-related indices, the carbon pool index and the carbon management index were greater at the deeper depth, than that in the shallower soil, suggesting lesser vulnerability of the soil organic carbon pool to modifications in the deeper layer. This is probably related to the more anaerobic conditions in these layers, limiting decomposition of organic matter. However, no effect of the soil depth was observed for the carbon lability index (Table 2). The effect of the interaction land-use×soil depth was not significant for any of the measured characteristics.

4 Conclusion

Overall, this study reveals that the long-term regime of moderate stubble grazing in continuous rain-fed wheat agro-systems does not degrade soil quality, nor reduce soil organic carbon pools, nor considerably decrease crop yields. It seems that livestock trampling during the summer, when the soil is dry, does not result in soil compaction and soil structure deformation. Moreover, for some of the indicators, the wheat under moderate stubble grazing treatment revealed somewhat better soil quality than that under wheat with entire stubble retention. Of special importance were the differences in carbon pool index and carbon management index, suggesting smaller adverse effects of land-use change on the soil organic carbon pools in croplands prone to moderate stubble grazing. Consequently, it seems that dryland agro-pastoral systems, where livestock moderately graze the wheat stubble during the dry season, could be considered a sustainable practice.

Yet, the specific effects of the stubble consumption and trampling action, and the mechanisms by which the wheat stubble and livestock feces are decomposed, as well as their effects on the soil organic carbon pools and dynamics, should be further investigated. Regardless, further studies have to assess the optimal rate of stubble retention, which will enable maximization of economic benefits while not degrading soil quality. Apart from that, the relatively low yields under both of the wheat treatments for most of the years during the last two decades should be of concern. Therefore, in the long run, soil fertility should be sustained through adequate nutrient management that could potentially increase the productive capacity of these agro-ecosystems.

Acknowledgments The authors are grateful to the JCA Charitable Foundation, which partially funded this study. Also, the authors thank the helpful and constructive comments made by two anonymous reviewers and the Editor-in-Chief on a previous version of the manuscript, which substantially improved its final version.

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