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Soil and crop management and biomass removal effects on soil organic matter content in Hungary

Greater use of biomass for bioenergy has increased the need to evaluate above ground biomass removal (BR) effects on soil quality components, especially soil organic matter (SOM). A multifactor, 40 year field experiment was conducted in Kompolt, Hungary on a carbonate-free, slightly acidic chernozem brown forest soil (USDA: Ustolls) with the objective of determining the effect of different management systems with concurrent removal of the above ground biomass on the SOM content of the 0-320 mm layer. A multifactor experiment composed of treatments involving different crop rotation (CR), beef manure application, mineral fertiliser application, above ground BR (vs. biomass incorporation, BI) and lucerne management options for different rotations are the basis of this study. CR had no significant effect on SOM content. Management options that included a four year lucerne stand produced significantly higher SOM content in five out of six fertiliser and biomass management combinations. Continuous manure applications and manure + NPK fertiliser resulted in a significantly greater SOM content than management options that minimised or eliminated fertiliser or manure additions. SOM content for different soil amendments and biomass treatments ranked: BR < NPK + BR < BI < manure + BR = NPK + manure + BR with SOM contents of 2.75 < 2.82 < 2.87 < 2.92 per cent (w/w) respectively. Manure had the most profound effect because its significance was most consistent across a range of management combinations and years. The results suggest that agricultural management systems that include lucerne and manure application have the potential to sustain SOM content with concurrent above ground BR in continental climates on Ustolls with near level topography.

Keywords: biomass, bioenergy, soil organic matter, soil management

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Introduction

The U.S. government 'Vision for Bioenergy and Biobased Products in the United States' set a goal that 5 per cent of power, 20 per cent of transportation fuels and 25 per cent of chemicals will be produced from biomass by 2030 (DOE, 2003). This goal is equivalent to 30 per cent of current national petroleum consumption and will require more than one billion dry UK tons (1.016 billion dry tonnes) of biomass feedstock annually. Similarly, the European Union (EU) Directive on the promotion of the use of energy from renewable sources (EC, 2009) includes a target of a 20 per cent share of renewable energy in energy consumption in the EU and differentiated national overall targets by 2020. According to projections, by 2020 biomass is expected to contribute about two thirds of the renewable energy. The primary agricultural biomass resources in the U.S. and Europe include crop residues from major crops – maize stover and small grain straw, grains, perennial grasses and perennial woody crops (Scarlat *et al*., 2010; Scarlat *et al*., 2011; Karlen *et al*., 2011; Clark *et al*., 2013; Meki *et al*., 2013).

Soil organic matter (SOM) is a soil quality indicator upon which agricultural production is dependent, while agricultural practices influence it (Larson and Pierce, 1994). Studies have shown that SOM content is directly related to the amount of residue applied to the soil (Rasmussen *et al*., 1980; Robinson *et al*., 1996; Dalzell *et al*., 2013; Kludze *et al*., 2013). Barber (1979) showed that above ground biomass removal (BR) negatively affects SOM levels. Therefore, it is reasonable to assume that SOM will decrease if residues are removed and that large scale above ground BR can degrade our soil resources. Moreover, accelerated erosion can increase SOM loss from unprotected soil surfaces.

Decreases in SOM can however be fully or partially mitigated with appropriate management such as reduced tillage, improved crop nutrition, organic amendments, cover crops and perennial vegetation (Janzen *et al*., 1998; Bruce *et al*., 1999; Dalzell *et al*., 2013; Zhao *et al*., 2013). Several studies have evaluated SOM content change as a function of different tillage and cropping systems (Mahboubi *et al*., 1993; Reicosky *et al*., 1995; Hunt, 1996; Rasmussen *et al*., 1998; Deen and Kataki, 2003), crop management (Halvorson *et al*., 2002; McConkey *et al*., 2003) with cover crops and legumes (Drinkwater *et al*., 1998; Fortuna *et al*., 2003), mineral fertiliser application (Halvorson *et al*., 1999; Russell *et al*., 2005), farmyard and green manure application (Sommerfeldt *et al*., 1988; Nardi *et al*., 2004; Sisti *et al*., 2004) and residue management (Rasmussen *et al*., 1980; Bohm *et al*., 2002). Most of these studies investigated several combinations of the above factors in different climates and soils such as in the semi-arid Pacific Northwest (Rasmussen *et al*., 1998); in Canadian prairie soils (McConkey *et al*., 2003); in the sandy southeastern Coastal Plain (Hunt *et al*., 1996); or in the Midwest (Russell *et al*., 2005).

Results from the long-term Morrow Plots in Illinois (Fenton *et al*., 1999) showed that crop rotation along with appropriate fertilisation was an important factor in achieving the highest crop yields and the highest soil N and organic C levels during 70 years of management (Odell *et al*., 1984). Changes in SOC (soil organic carbon) are linearly related to the annual C input rates associated with N fertility management, whereas legume-cereal crop sequences maintained SOM content without external N fertilisation in southern Wisconsin (Vanotti *et al*., 1997). Clapp *et al*. (2000) examined the interaction among maize stover harvest, N fertilisation and SOC dynamics in a 13 year experiment in Minnesota. They reported that SOC in the no-till plots with maize stover harvest remained unchanged, while that with the stover returned increased. They also found that the N fertilisation effects on SOC were most evident when the maize stover was returned to no-till plots.

Long term experiments are the best means to empirically study soil management impacts on SOM content. As described previously, several of these studies exist and have been extensively analysed. However, such data published from long term research that investigates the interactions of residue harvest with various management practices such as crop rotations, mineral and manure fertiliser application are missing in the literature. The objective of this paper was to identify management practice impacts on SOM content with concurrent above ground biomass removal using long term field data with a broad range of fertiliser and crop management practices.

Materials and methods

Field site

The research was established at the Rudolf Fleischmann research station at Kompolt, Hungary in 1962. Kompolt is located 47°45’ N and 20°15’ E, about 110 km NE of Budapest and 25 km NE of Gyöngyös. The elevation of the research station is 125 m above sea level. The region has a temperate continental climate with the mean annual air temperature of 10°C. The mean annual precipitation is 549 mm of which 309 mm fall within the growing season although dry spells are common. Mountain ranges NW and NE from Kompolt influence the research station’s climate. The topography is nearly level and the water table depth is 11-12 m (Tóth *et al*., 1998). The soil is a carbonate-free, slightly acidic chernozem brown forest soil (USDA: Ustolls, Németh *et al*., 2002). Initial soil measurements performed in 1961 indicated that the average SOM content was 2.87 per cent (w/w) and the pH was 5.5 in the field plot area. The soil NH_4^+ content was 6.4 ppm, $NO_3^- + NO_2$ was 5.4 ppm, P_2O_5 was 28.0 ppm and the K_2O content was 216 ppm in the 0-250 mm depth.

Sampling procedure

A multifactor 40 year-long experiment was established in 1962 with three crop rotations (CR), 12 fertiliser and biomass management (FBM) treatments and three fertiliser and lucerne (*Medicago sativa* L.) management (FLM) treatments. Each treatment was replicated four times. Based on the objectives of this paper the authors were interested in six of the 12 FBM treatments and only those will be introduced and discussed in this paper. In this experiment, a four year period was considered a sequence. During the experiment conventional soil tillage practices were used and above ground biomass was removed by hand. Farmyard beef manure with wheat straw as bedding was applied to selected plots at a rate of 35.2 Mg ha^{-1} wet weight (8.5 Mg ha^{-1} dry weight). Manure supplied 0.176 Mg N ha^{-1} (Kismányoky, 1994). The mineral fertiliser applied was a 0.236 Mg ha^{-1} NPK mix that contained 0.088 Mg N ha^{-1}, 0.044 Mg P_2O_5 ha^{-1}, and 0.104 Mg K_2O ha^{-1}. Based on the local practices, green pea vine residue and spring barley straw was always removed from the plots. Biomass removal (BR) or biomass incorporation (BI) from other crops in the rotations is the basis for the BR treatments in this study. Manure was applied in the first year within each crop rotation sequence (once every four years).

The three different CR (main plots) were: (a) maize (*Zea mays* L.) monoculture; (b) maize-maize-wheat- (*Triticum aestivum* L.) wheat; and (c) maize-spring barley- (*Hordeum vulgare* L.) green pea- (*Pisum arvense* L.) wheat. The different FBM treatments were used to split the main plots and the different FLM treatments were used as the second split. The three FLM treatments within the different rotations were: (a) a four year sequence with annual fertiliser application followed by a four year sequence with no soil amendments; (b) annual fertiliser application; and (c) a four-year sequence of annual fertiliser application followed by a four-year sequence of lucerne.

The lucerne stands received minimal amounts of N fertiliser in the first year to establish seeding while P and K were applied in sufficient quantities to meet the four year growth requirement. The lucerne was cut and removed from each plot three or four times annually. Green pea received only 73 per cent of the N fertiliser applied to the other crops. Plots were 54 m^2 (6 m x 9 m). Soil samples for SOM analysis were collected every fourth year of the experiment (0-320 mm). The SOM analyses were performed using Turin’s methodology (Belchikova, 1965). For this study four sampling years (SY) 1969, 1977, 1981 and 2001 were used. SOM content is expressed as per cent on a gravimetric basis.

Statistical analysis

The statistical design was a split-split-plot in time. The effects of CR were tested on the main plots, the effects of FBM were tested on the split plots, and the effects of FLM were tested on the split-split plots. For statistical analyses, blocks were treated as having random effects, while CR, FBM, FLM and SY as fixed. Interactions with random block effects were used as error terms. Statistical analysis was performed using SAS version 9.1 (SAS Institute, 2003). Means were obtained with the least square mean (LSM) statement and significant interactions that occurred were evaluated using the LSM procedure. Least significant difference (LSD) statements allowed mean comparisons for FBM to examine the impact of mineral fertilisation, manure application and BI on SOMC. Treatment differences were considered significant at a probability level of 0.05.

Results and discussion

Table 1 shows the analysis of variance for gravimetric SOM content.

Table 1: Analysis of variance for gravimetric SOM content.

Source	DF	Type III SS	Mean Square	F value	Pr > F
Block	3	0.42	0.14	5.69	0.0008*
CR	2	3.25	1.63	2.78	0.1397
FBM	5	2.94	0.59	6.46	0.0001*
CR x FBM	10	0.89	0.09	0.98	0.4755
FLM	2	3.86	1.93	96.71	< 0.0001*
CR x FLM	4	0.09	0.02	1.19	0.3208
FBM x FLM	10	0.56	0.06	2.83	0.0037*
CR x FBM x FLM	20	0.29	0.01	0.72	0.7987
SY	3	0.57	0.19	7.61	< 0.0001*
CR x SY	6	1.00	0.17	6.73	< 0.0001*
FBM x SY	15	1.07	0.07	2.88	0.0002*
CR x FBM x SY	30	0.80	0.03	1.07	0.3653
FLM x SY	6	0.20	0.03	1.34	0.2395
CR x FLM x SY	12	0.16	0.01	0.53	0.8927
FBM x FLM x SY	30	0.34	0.01	0.46	0.9942
CR x FLM x FBM x SY	60	0.51	0.01	0.34	1.0000

* Significant at probability level, $P<0.05$
Abbreviations: CR: crop rotation; FBM: fertiliser and biomass management treatment; FLM: fertiliser and lucerne management treatment; SY: sampling year

Fertiliser and lucerne (FLM) management

Differences between FLM treatments depended on FBM treatments. FLM that included a four year lucerne stand, even though top growth was removed, produced significantly greater SOM content in five out of six FBM treatments (Table 2 column c vs. a and b). Similar results were observed in Iowa (Robinson *et al*., 1996; Russell *et al*., 2005) and in Hungary (Tóth and Kismányoky, 2001; Krisztián and Holló, 1995) where cropping systems with lucerne proved to be viable management options for increasing SOM content. The treatment that included BI and NPK application showed no differences in SOM content between annual fertilisation application (2.88 per cent SOM) and lucerne stand (2.94 per cent SOM). It appears that the effect of continuous BI on SOM content was similar to the effect of producing lucerne.

Treatments in which biomass was removed and manure applied had significantly higher SOM content when fertiliser was applied annually (2.90 and 2.94 per cent SOM) than when it was applied in four of the eight years (2.83 and 2.81 per cent SOM). In summary, treatments with lucerne stands and continuous manure application had the greatest positive effect on SOM content. Tóth and Kismányoky (1997) found similar results in Hungary in a long term experiment where they investigated the effects of fertilisation and crop rotation on SOM content.

Fertiliser and biomass (FBM) management

Differences in SOM content between years depended on FBM. The control treatment showed a decline in SOM content in 1981 and in 2001 (2.67-2.71 per cent SOM content) compared to 2.81 per cent SOM content in 1969 (Table 3). The BI+NPK treatment in 1969 (2.87 per cent SOM content), manure+BR and NPK+manure+BR in 1977 (2.91), manure+BR in 1981 (2.90), and NPK+manure+BR in 2001 (3.04) demonstrated the greatest SOM content. Application of manure+BR and manure+NPK+BR showed the greatest SOM content among the treatments in 1977, 1981 and 2001. However, SOM content was not statistically different across years in treatments with manure+BR. This suggests that treatments with manure+BR were able to maintain relatively high SOM contents (compared with the other treatments) but were not able to increase these values over years. On the other hand, in treatments with manure+NPK+BR, SOM content remained relatively high and tended to increase over the second half of the experiment (2.88-3.04). Similarly to treatments with manure+BR, treatments with NPK+BR were unable to increase SOM content over the years. When FBM treatments were averaged over the effects of SY and FLM, it showed that the control treatment produced the lowest (2.75) and NPK+manure+BR the greatest (2.92) SOM content.

Table 2: Soil organic matter content in different fertiliser and biomass management (FBM) and fertiliser and lucerne management (FLM) treatments from the last sampling time (2001), %.

FBM			FLM			Mean
NPK Mg ha^{-1}	Manure Mg ha^{-1}	Biomass	a*	b**	c***	
0	0	BR	2.70d	2.67d	2.88e	2.75
0.236	0	BR	2.76d	2.79d	2.91e	2.82
0	35.2	BR	2.83d	2.90e	3.00f	2.91
0.236	35.2	BR	2.81d	2.94e	3.02f	2.92
0	0	BI	2.82d	2.84d	2.95e	2.87
0.236	0	BI	2.82d	2.88de	2.94e	2.88
Mean			2.79	2.84	2.95	2.86

Within rows, values followed by the same letter are not significantly different using LS Mean test; $P<0.05$; BR: biomass removed; BI: biomass incorporated; *: a sequence (four year period) with annual fertiliser application followed by a sequence with no soil amendments; **: annual fertiliser application; ***: a sequence (four year period) of continuous fertiliser application followed by a sequence of lucerne stand
Source: own data

Table 3: Soil organic matter content in different fertiliser and biomass management (FBM) treatments and sampling year.

FBM treatments			Sampling year				Mean
NPK Mg ha^{-1}	Manure Mg ha^{-1}	Biomass	1969	1977	1981	2001	
0	0	BR	2.81d	2.82d	2.67ef	2.71f	2.75
0.236	0	BR	2.82d	2.81d	2.80d	2.85d	2.82
0	35.2	BR	2.89d	2.91d	2.90d	2.94d	2.91
0.236	35.2	BR	2.88d	2.91d	2.86d	3.04e	2.92
0	0	BI	2.92d	2.88de	2.83ef	2.85df	2.87
0.236	0	BI	2.87d	2.88d	2.84de	2.93df	2.88
Average			2.86	2.87	2.82	2.89	2.86

Within rows, values followed by the same letter are not significantly different using LS Mean test; $P<0.05$; BR: biomass removed; BI: biomass incorporated
Source: own data

Crop rotation

Differences in SOM content between years depended on the CR. Mean SOM content was the lowest for maize monoculture (2.77 per cent SOM content) and the highest for two- or four-crop rotations (2.90) (Table 4). Similar results were observed in the Morrow Plots in Illinois where crop rotation retarded the decline in SOC (Odell *et al*., 1984), in Nebraska where after eight years rotation significantly increased SOC across all cropping systems (Varvel, 2006) and in Hungary where crop rotation increased SOM content compared to monoculture maize (Tóth and Kismányoky, 2001). Robinson *et al*. (1996) found that maize monoculture was the most detrimental to SOC in different soil management systems in Iowa.

Table 4. Soil organic matter content in different crop rotations and sampling years, %.

Crop rotation	Sampling year				Mean
	1969	1977	1981	2001	
Monoculture	2.78d	2.84e	2.66f	2.81de	2.77
Two crop rotation	2.91d	2.90d	2.89d	2.91d	2.90
Four crop rotation	2.89d	2.88de	2.91d	2.94df	2.90

Within rows, values followed by the same letter are not significantly different using LS Mean test. $P<0.05$
Source: own data

The impact of soil amendments on soil organic matter content

The impact of mineral fertilisation on SOM content was established by comparing mean values of NPK + BR with the control (no fertiliser application + BR) treatment (Table 3). Mean SOM content was greater with mineral fertiliser application (2.82 per cent SOM content) than without soil amendments (2.75 per cent SOM content). This trend held in sampling years 1981 and 2001 when differences were statistically significant. Similar results were found in Iowa (Robinson *et al*., 1996) and in Hungary (Krisztián and Holló, 1995) where NPK treatments increased SOM content compared with no fertiliser application. The impact of manure application on SOM content was established by comparing mean values of manure + BR with the control (no soil amendment + BR) treatment. Mean SOM content was greater with manure application (2.91) than without soil amendments (2.75) and this trend was consistent across the years with significant differences being observed in the last two sampling times. There were similar results from the Broadbalk experiment at Rothamsted in the UK where additions of farmyard beef manure increased total C content compared to the control treatment (Blair *et al*., 2006). Of note is that manure application alone resulted in greater mean SOM content than application of NPK.

The impact of BI on SOM content was determined by comparing mean values of SOM content of no fertiliser application + BI with the control (no fertiliser application + BR) treatment. The mean SOM content was greater with BI (2.87 per cent SOM) than with BR (2.75 per cent SOM). This trend was true for each SY although differences within years were not statistically separable. Similar results were found in Indiana (Barber, 1979) and Minnesota (Allmaras *et al*., 2004) where maize stalk residue removal decreased SOM when compared with residue returned to the soil. Effects of both mineral and organic amendment application on SOM content were established by comparing mean values of NPK + manure + BR with NPK + BI. The mean SOM content was greater for mineral fertiliser and manure application followed by BR (2.92 per cent SOM content) than for mineral fertiliser alone followed by BI (2.88 per cent SOM content).

The impact of soil amendments including BI were determined by comparing mean values of NPK + BR with manure + BR and no soil fertiliser application + BI with NPK + BR. SOM content for manure + BR was significantly greater than for NPK + BR consistently across years. On the other hand SOM content for no soil fertiliser application + BI was statistically similar for most SY with NPK + BR. These results show that the value of biomass as soil amendment was equivalent to that of mineral fertiliser but less than that of manure amendment in increasing SOM content. There were no statistical differences between NPK + BI (2.88) and BI + no fertilisation (2.87); between NPK + manure + BR (2.92) and manure + BR (2.91); and manure + BR (2.91) and NPK + BI (2.88). The results indicate that the ranking of different management treatments on SOM content was: BR + no fertilisation < NPK + BR < BI + no fertilisation < manure + BR = NPK + manure + BR with SOM content of 2.75 < 2.82 < 2.87 < 2.92 respectively.

The impact of soil organic matter on bulk density

It is well recognised that organic matter content affects soil physical properties. An increase in soil C content increases aggregation, decreases bulk density, and increases water holding capacity and hydraulic conductivity (Williams and Cooke, 1961; Tiarks *et al*., 1974; Gupta *et al*., 1977). In some soils, organic matter has a dominating effect on soil bulk density (Curtis and Post 1964; Saini, 1966). Although studies similar to ours on SOM content determined soil C differences among treatments based on concentrations (Barber, 1979; Odell *et al*., 1984; Reicosky *et al*., 1995), unless this effect is considered, quantitative SOM data based on a percentage of total soil weight can be misleading (Adams, 1973). If the study goal is to estimate treatment effects on the mass of SOM, drawing conclusions based on the values of concentration are subject to error if bulk density varies among treatments.

Adams (1973) suggested that the SOM content could be used to predict soil bulk density. We used Adams` equation to estimate bulk density differences among treatments simply to see the potential relative impact of the SOM content differences observed:

$$BD = \frac{100}{\left(\frac{\%OM}{OMBD}\right) + \left(\frac{100 - \%OM}{MBD}\right)} \qquad (1)$$

where BD is bulk density (g cm^{-3}), OM is organic matter (per cent), OMBD is bulk density of organic matter (g cm^{-3}) and MDB is bulk density of mineral matter (g cm^{-3}). OMDB was assumed to be 0.244 g cm^{-3} (Mann, 1986; Post and Kwon, 2000). MBD is usually assumed to be 2.65 g cm^{-3}, which was used in Adams` calculation. We assumed that soil BD was 1.3 g cm^{-3} in the experiment. We further assumed that the per cent OM was 2.86, the average OM content across treatments at the beginning of the experiment. BD then was calculated for treatments with the lowest and greatest percent SOM.

The results show that a difference in BD between those treatments would be 0.027 g cm^{-3}. The real influence of SOM, however, could be masked by the effect of soil structure on bulk density (Adams, 1973). In that conventional tillage practices were used in all treatments – for this region that means multiple passes starting with an autumn mouldboard ploughing operation – the differences in structure due to the relatively small differences in SOM content seems quite unlikely, although it was not measured in this experiment. Overall, we concluded that the difference in BD that may have existed and could have influenced the conclusions would have been due only to changes in SOM content, and the greatest influence would be about 0.026 g cm^{-3}. According to the literature, the spatial variability in BD measurements in a common treatment is about 10 per cent of the mean bulk density measure (Aljibury and Envans, 1961; Warrick and Nielsen, 1980) – a value which is much greater that our estimate of SOM content bulk density impact between treatments. Therefore, we concluded that the results of this study using SOM content rather than a calculated mass of SOM between treatments truly reflects treatment impacts on SOM changes.

Implications and limitations

Elevated global demand for agricultural products, in particular crop biomass for biofuels, bioproducts and livestock feed and bedding, favours short-term agricultural economics, but threatens soil quality and long term economics due to depletion of SOM under many management scenarios (Cruse *et al.,* 2009). Numerous studies previously cited illustrate a sound understanding of crop management impacts on SOM, especially when crop residues are retained on the field and/or when organic matter is returned to the field as manure following use in animal based enterprises. Unfortunately, off farm markets are increasingly moving crop biomass into production facilities that have no or little economic incentive to return organic matter or organic matter by-products to the field of origin. This study substantiates previously recognised science regarding soil and crop management impacts on SOM content with biomass returned to the soil to biomass removal systems.

This study suggests SOM maintenance will be a challenge if some form of above ground biomass is not returned to the soil, especially with monocultures of maize. Diversifying a row crop operation such that lucerne is included within the rotation seems to offset the negative SOM impact of long term maize biomass harvest. Realistically, however, getting farmers to diversify existing row crop dominated enterprises has been futile in areas such as the U.S. even though more diverse farming operations have been shown to be as profitable per unit land area as continuous row cropping with maize and soya (*Glycine max*) (Davis *et al.,* 2012).

While long term studies such as this are valuable, they have limitations. Technology change can be rapid, thus caution is advised when making direct application of results obtained from studies initiated decades ago to current farming systems. For example, no-till methods and use of modern day maize cultivars with significantly higher production potential than older cultivars could modify SOM dynamics and result in different SOM contents than observed in this study. However, in the absence of literature addressing the interaction of SOM dynamics with variables such as tillage and genetics, one should assume that absolute values of SOM content would change, but that relative impacts of treatments would remain.

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