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# Compost as an Option for Sustainable Crop Production at Low Stocking Rates in Organic Farming

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**Abstract:** Mixed-crop-livestock farms offer the best conditions for sustainable nutrient management in organic farming. However, if stocking rates are too low, sustainability might be threatened. Therefore, we studied the development of soil organic matter and nutrients as well as crop yields over the first course of a new long-term field experiment with a mimicked cattle stocking rate of 0.6 LU $ha^{-1}$, which is the actual average stocking rate for organic farms in Germany. In the experiment, we tested the effects of additional compost application to improve organic matter supply to soils, and further, potassium sulfate fertilization for an improved nutrition of fodder legumes. Compost was made from internal resources of the farm (woody material from hedge-cutting). Soil organic matter and nutrient stocks decreased in the control treatment, even though yield levels, and thus nutrient exports, were comparably low. With compost application, soil organic matter and nutrient exports could be compensated for. At the same time, the yields increased but stayed at a moderate level. Potassium sulfate fertilization further improved N yields. We conclude that compost from internal resources is a viable solution to facilitate sustainable organic crop production at low stocking rates. However, we are aware that this option does not solve the basic problem of open nutrient cycles on the farm gate level.

**Keywords:** long term field experiment; sustainable crop production; nutrient balances; legume nutrition



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## 1. Introduction

Soil organic matter is recognized as a key factor of soil fertility [1]. For this reason, the supply of soils with organic matter was always a major concern in organic agriculture. Meanwhile, it was shown that organic farming in fact leads to higher soil organic matter levels than conventional management [2]. However, a sufficient supply of soils with organic matter is not an effect of organic farming per se, but of the specific structure of organic systems. Leithold et al. [3] emphasized that fodder legumes and cattle manure are the basic factors for a sufficient supply of soils with organic matter. These factors must balance the loss of soil organic matter in turnover. If the supply of soil with organic matter is too low to meet the specific requirements, SOM levels might decrease even under organic management. This situation was observed in the OAFEG long-term field experiment in Germany that is designed to study the effects of mixed, as compared to stockless organic farming [4]. Under the conditions of this experiment, SOM stocks increased under the mixed farming treatment, but stayed unchanged or even decreased under the two stockless treatments. In a modeling study, Brock et al. [5] calculated that the actual average soil organic matter balance of organic farming in Germany was slightly negative, as the mean animal stocking rate was only 0.63 LU per ha at that time. Even though this result should not be overrated due to the high uncertainty of the calculation, it seems necessary to further study soil organic matter changes under organic management with low stocking rates or even stockless systems. If manure availability is too low, farmers will need to utilize further sources of organic matter. Here, green manure and compost are the most important options.

The demand for organic matter to maintain or even increase soil organic matter stocks is dependent on site conditions, management history, and actual management [6]. Organic inputs of plant roots and residues, animal manure, and other material must balance the loss of organic matter in turnover. As organic matter supply and turnover are directly linked to N supply in organic farming, the demand for organic matter is greater with higher yield levels (of non-legumes), due to the export of mineralized N [3].

Compost is reported as a viable option to increase soil organic matter and soil health [7,8]. In principle, composting is the biological decomposition of organic residues [9]. Compost can be made from different substrates, e.g., municipal waste, sewage sludges, plant residues/green waste, farmyard manure, or biogas production residues. Farm compost, as applied in the field experiment reported in this study, is carried out individually in farms, depending on the available materials. However, Lehtinen et al. [10] found that impacts on soil properties and crop yields were not significantly different between the composts made from municipal waste, sewage sludge, green waste, and farmyard manure in a long-term field experiment, even though the macronutrient inputs differed. Further, microbial biomass and the composition of the microbial community differed between the treatments [11].

In general, compost application builds up soil organic matter [12] and enhances crop yields moderately in the short run [13]. In the long run, the build-up of soil organic matter further improves the growing conditions for arable crops and thereby further increases yields [14,15].

The biological N fixation (BNF) is an important source of N for organic crop rotations because mineral sources of N fertilizers that are allowed for organic farming are limited. Especially in organic agriculture, BNF is preferred due to different advantages, as compared to mineral N sources like higher N use efficiency of the plants and decreased volatilization, denitrification, and leaching [16]. Therefore, nitrogen fixing legumes like clover and lucerne are usually placed at the beginning of organic crop rotations and act as drivers for the subsequent crops. However, clover and lucerne react particularly sensitively to the deficiencies of P, K, and S. Although several processes and mechanisms about the dependency of legume growth to the listed elements remain unclear [17] it is evident that a good supply improves crop growth and health. It is also known that legumes that acquire N by BNF have a higher demand of P, K, and S, as compared to those that rely on soil N only [18,19]. It is generally accepted that when the host plant growth is reduced due to deficiencies of P, K, or S, an N-feedback is triggered so that the nodule development and activity is reduced. This mechanism can also be induced by plant diseases and pathogens, as well as abiotic stresses like drought, toxic levels of salt, or heavy metals [20–22].

In this study, we showed the development of crop yields and soil nutrients and organic matter over the first crop rotation in a long-term field experiment, under conditions of organic farming (more specifically—biodynamic farming). The experiment mimicked a mixed farm with a stocking rate of 0.6 LU cattle per hectare, which corresponded to the average stocking rate of organic farms in Germany. In this experiment, we compared a fertilization regime that was based on the available cattle manure with a regime that additionally utilized a farm compost made from available plant residues on the farm. Further, we examined the effect of potassium sulfate application, which was owed to the fact that the experiment was located on a potassium-fixing soil.

As the field experiment is still in an early stage, we can only study the short-term effects and development factors, rather than development trends. In this stage, we expect the positive effects of compost application on crop yields, and increased biological N fixation rates in legumes with potassium sulfate application. Further, we want to study the impact of the fertilization regimes on soil nutrient and organic matter balances. This is of high relevance in organic farming, as crop production is largely dependent on soil fertility.

## 2. Materials and Methods

We analyzed crop yields and the development of nutrient (N, P, K, S) and organic matter stocks in the soils under the four treatments, in a long-term field experiment on a luvisol, under conditions of biodynamic farming. Further, we calculated nutrient and soil organic matter balances to support the assessment of factor treatment effects, and modelled opportunities to improve organic matter supply to soils.

### *2.1. Experimental Site and Trial Design*

The long-term field trial was initiated in 2010 Germany, Hesse (50°11′39.0″ N 8°45′09.5″ E) at 120 m above the sea level. It is maintained by the on-farm research and breeding department Dottenfelderhof. The soil type is a Haplic Luvisol with Silt loam from loess [23]. The average precipitation is 630 mm per year with an average temperature of 9.4 °C.

The farm was converted from conventional to biodynamic agriculture in 1968. In the time of conventional practice, sugar beet was cropped as a monoculture for many years. Since the conversion, the crop rotation consisted of a two times six year rotation with a legume/grass mixture in year one and two; winter wheat in year three; winter rye in year four; root crops in year five; and a spring cereal in year six. The legume/grass mixture alternated between clover/grass and alfalfa/grass from one six-year cycle to the next. Root crops varied widely and could be maize, potatoes, carrots, or other. The spring cereals are usually oats or spring wheat. In the rotation under study, it is important to notice that fodder maize was planted instead of winter rye in 2015 and clover/grass was ploughed and reseeded in 2013, because of drought and winter damage.

All treatments receive the same biodynamic preparations [24], i.e., BD 500 and BD 501 spray, at least once a year each. The compost used for the experiment was prepared with the usual biodynamic compost preparations and was made on site.

The trial was initiated in spring 2010 as a one factorial Latin square design with four treatments on plots of 48 $m^2$ gross area (6 × 8 m) and 29.25 $m^2$ net area (4.5 × 6.5 m). On all plots, an equivalent livestock unit (LU) of 0.6 cattle deep litter (06M) was applied. Treatments 2 and 4 were treated with potassium sulfate (K), and treatment 3 and 4 with biodynamic compost (BD).

1. Control (06M).
2. Potassium sulfate (06M + K).
3. Biodynamic plant-based compost (06M + BD).
4. Biodynamic plant-based compost + potassium sulfate (06M + BD + K).

The cattle deep litter was a fermented manure from the farms' dairy cow herd. A total of 70% of the cow manure was distributed evenly, daily in the stable, and covered with straw. Cow pat pit preparation was added daily and compost preparations were applied once a month. The deep litter was harvested after the rye harvest and worked into the soil before the root crops were planted.

Potassium sulfate was produced by the fertilizer company K + S, under the tradename "Kalisop" and consisted of 50% water-soluble potassium oxide ($K_2O$) and 45% water-soluble sulfur trioxide ($SO_3$).

The biodynamic compost consisted of 85–90% green chop, 5–8% cow manure, and 5–7% soil. To speed up the process, the material was mixed daily in the first week and prepared with the cow pat pit during this time. After that, the single biodynamic compost preparations were added for the first time. Whey from the farm dairy or water was added to keep the right moisture content, which should be over 60% to avoid overheating and thus losses of nutrients, because the initial material was usually too dry. To protect the compost from rain, it was covered with a compost membrane. After the initial week and during the following half year process of composting, the compost pile was turned three to four times. After three months, the biodynamic compost preparations were added a second time.

Table 1 shows that the climatic water balance according to Haude [25] was negative from 2012 until 2015, and was positive in 2016 and 2017.

**Table 1.** Mean annual temperature, annual precipitation, and climatic water balance [25] during the investigation period.

| Year | Mean Annual Temperature (°C) | Total Annual Precipitation (mm) | Annual Climatic Water Balance (mm) |
|---|---|---|---|
| 2012 | 10.6 | 572.8 | −153.8 |
| 2013 | 10.5 | 664.4 | −10.2 |
| 2014 | 12.0 | 669.7 | −72.5 |
| 2015 | 11.7 | 434.7 | −408.4 |
| 2016 | 10.7 | 729.0 | 159.8 |
| 2017 | 11.0 | 717.9 | 157.3 |

### 2.2. Fertilizer and Manure Application

The applied amounts of manure and fertilizer are shown in Table 2, except an application of 2 Mg ha$^{-1}$ lime ($CaCO_3$ with 56% CaO) on all treatments in November 2009, because the pH was too low at the start of the experiment. The cattle deep litter was applied on all treatments before planting of root crops once in a 6-year rotation.

**Table 2.** Crop rotation, amounts of organic amendment, and total nutrient amounts (kg ha$^{-1}$) applied with all fertilizers (cattle deep litter, compost, and $K_2SO_4$).

| Year | Crop | Treatment | Cattle Manure [1] | Compost [2] | N | P | K [3] | S [3] |
|---|---|---|---|---|---|---|---|---|
| | | | Mg ha$^{-1}$ fresh matter | | kg ha$^{-1}$ dry matter | | | |
| 2010 | potato | 06M | 40.0 | | 208.0 | 120.6 | 271.9 | 45.0 |
| | | 06M + K | 40.0 | | 208.0 | 120.6 | 671.9 | 218.5 |
| | | 06M + BD | 40.0 | 30.0 | 344.2 | 150.2 | 383.8 | 67.3 |
| | | 06M + BD + K | 40.0 | 30.0 | 344.2 | 150.2 | 656.6 | 185.6 |
| 2011 | oat/clover grass | 06M | | | | | | |
| | | 06M + K | | | | | 400.0 | 173.5 |
| | | 06M + BD | | 15.0 | 51.7 | 17.2 | 50.7 | 8.5 |
| | | 06M + BD + K | | 15.0 | 51.7 | 17.2 | 400.0 | 160.1 |
| 2012 | clover grass | | | | | | | |
| 2013 | clover grass | | | | | | | |
| 2014 | winter wheat | 06M | | | | | | |
| | | 06M + K | | | | | | |
| | | 06M + BD | | 30.0 | 87.9 | 26.6 | 112.3 | 13.5 |
| | | 06M + BD + K | | 30.0 | 87.9 | 26.6 | 112.3 | 13.5 |
| 2015 | fodder maize | 06M | | | | | | |
| | | 06M + K | | | | | 300 | 130.3 |
| | | 06M + BD | | 30.0 | 98.4 | 59.3 | 269.6 | 29.5 |
| | | 06M + BD + K | | 30.0 | 98.4 | 59.3 | 419.6 | 94.6 |
| 2016 | red beet | 06M | 35.0 | | 168.3 | 41.3 | 231.5 | 19.7 |
| | | 06M + K | 35.0 | | 168.3 | 41.3 | 431.5 | 106.6 |
| | | 06M + BD | 35.0 | 30.0 | 294.9 | 92.4 | 426.1 | 40.4 |
| | | 06M + BD + K | 35.0 | 30.0 | 294.9 | 92.4 | 476.1 | 62.1 |
| 2017 | spring wheat | 06M | | | | | | |
| | | 06M + K | | | | | 400 | 173.5 |
| | | 06M + BD | | 30.0 | 123.6 | 39.3 | 160.4 | 19.2 |
| | | 06M + BD + K | | 30.0 | 123.6 | 39.3 | 480.4 | 158 |

[1] cattle manure from deep litter; [2] compost = plant-based compost; [3] K and S was applied at the same time as the compost in 2010, 2011, 2015, 2016, and 2017 as $K_2SO_4$.

The amount was calculated to represent 0.6 LU $ha^{-1}$ and was applied in spring 2010, before planting of potatoes (40 Mg $ha^{-1}$) and in spring 2016 before planting of red beet (35 Mg $ha^{-1}$). The same amount of compost (30 Mg $ha^{-1}$) was applied on the 06M + BD and 06M + BD + K treatment in 2010 and from 2014 to 2017, after calculating the maximum allowed N amount by the German fertilizer regulation. In 2011, the applied amount of compost was 15 Mg $ha^{-1}$. Potassium sulfate was applied on the 06M + K treatment in three subsequent years from 2015 to 2017, in an amount that was derived from previous dosing tests.

### 2.3. Soil Samples and Chemical Analyses

Soil samples were taken every year after harvest or in autumn, for clover grass, from a soil depth of 0–30 cm. These were then mixed and sent to the laboratory "Hessisches Landeslabor" (LHL).

Soil organic carbon (SOC) were analyzed by combustion at 550 °C under $O_2$, using Leco® RC612 carbon analyzer. Total N were measured by the dry combustion method until 2012, according to DIN ISO 13878 [26], and afterwards according to DIN EN 16168 [27]. Total K, S, and P were determined by inductively coupled plasma optical emission spectrometry [28]. Soil pH was measured 1:10 in 0.01 M $CaCl_2$ [29]. Soil bulk density was calculated as the dry weight of soil divided by its volume and as a mean of replications at the end of the rotation [30].

### 2.4. Yield and Samples for Crop Nutrients

Clover grass was cut three times during the vegetation period at 12 June, 1 August, and 10 October 2012, and two times in 2013 at 19 June and 24 September. The harvest from the net plots was weighed to determine fresh matter yield. A 5 kg mixed sample of harvest was chopped and from this material 2 × 1 kg was dried at 105 °C in an oven, to determine dry weight yield. Samples for the analyses of nutrient content were taken from the chopped material.

In 2014, winter wheat cv. Butaro was harvested with a Hege 125 combine. Grain and straw were weighed separately for fresh matter yield. The straw was processed in an analogous manner to clover grass, for determination of dry weight and laboratory samples.

From maize cv. Colisee in 2015, grain was harvested on 9 September by hand. The straw was harvested one day later with a maize chopper. Maize straw was processed in an analogous manner to clover grass. Red beet cv. Robuschka was harvested on 14 September by hand. Stem and leaves were separated from the bulbs, and fresh matter yield was determined separately. From both portions, a mixed sample of 2 kg was taken and sent to the laboratory. Sping wheat cv. Heliaro was harvested on 4 August and processed in an analogous manner to winter wheat.

Crop nutrients (P, K, and S) were measured with X-ray fluorescence spectroscopy, according to VDLUFA Volume III [31]. Dry matter and N were determined according to ISO 12099 [32].

### 2.5. Soil Surface Nutrient Balance

The nutrient balances were calculated from 2012 until 2017, because this was a full cycle of the crop rotation, beginning with the legume-grass mixture, until the spring cereal.

The N, P, K, and S balances were annually estimated as the difference between nutrient input and nutrient output (kg $ha^{-1}$ $year^{-1}$):

$$\text{Nutrient budget} = \text{nutrient input} - \text{nutrient output} \quad (1)$$

Where the nutrient inputs included fertilization (deep litter manure, plant-based compost, and potassium sulfate) and crop seeds, the outputs included harvested aboveground biomass (main and side product).

For the N balance, the N inputs were extended by atmospheric N depositions, asymbiotic N fixation, and symbiotic N fixation. The N atmospheric deposition were estimated at 15 kg ha$^{-1}$ year$^{-1}$, and the asymbiotic nitrogen fixation were 5 kg ha$^{-1}$ year$^{-1}$.

The symbiotic N fixation was estimated according to the Stein-Bachinger [33]:

$$\text{Symbiotic N fixation} = (N_{shoot} + N_{root} + \text{stubble}) \times Leg_{share} \times Ndfa \tag{2}$$

where $N_{shoot}$ was calculated as the product of grass-clover biomass and the N concentrations. $N_{root + stubble}$ was calculated as the product of grass-clover biomass and the fix value of 0.75 for the root and stubble biomass, and the totally fixed root and stubble N (1.5%). For the $Leg_{share}$, we assumed the fix value 0.7 and for the Ndfa (nitrogen derived from the atmosphere) it was 0.8, respectively.

### 2.6. Soil Organic Matter Balance (HU-MOD)

The HU-MOD model [34,35] was developed as a decision support tool for application in farming practice. Unlike most other so-called humus balance methods, this model was conceptually able to analyze and predict soil organic matter changes [36]. The estimation of soil organic matter changes was based on the calculation of a coupled C and N balance in the soil–plant system. In principle, the model assumed that N in plant biomass could be used as a proxy for soil organic matter mineralization, if the N was supplied from other sources (here, atmospheric deposition, fertilizers, and—for legumes—biological nitrogen fixation) were considered. Thus, soil organic matter loss was calculated according to:

$$\text{SOMLOSS (kg SOM-N ha}^{-1}) = \text{NPB} - \text{NFIX} - \text{NDEP} - \text{NFTLZ} \tag{3}$$

NPB = N in total plant biomass (including roots), NFIX = N from biological fixation (legumes only), NDEP = N from atmospheric deposition, and NFTLZ = N from organic and mineral fertilizers.

SOM-N was transferred to SOM-C, based on the C:N ratio of the soil under assessment. Regarding the formation of new soil organic matter, the model applied a stoichiometric assumption, where the build-up of soil organic matter could be limited both by C and N availability. Again, the C:N ratio of the soil at the site under assessment was taken as a reference. Soil organic matter gain was therefore calculated according to:

$$\text{SOMGAIN (kg SOM-C ha}^{-1}) = \text{MIN(CREM; NREM} \times \text{SITECN)} \tag{4}$$

CREM = C from organic material (including plant roots), NREM = remaining N in the soil from organic material (including plat roots) and other inputs after consideration of losses, SITECN = reference C:N ratio of the soil at the site under assessment (topsoil C:N ratio was used as a proxy).

In the calculation of remaining C and N for the soil organic matter build-up, organic C and N inputs as well as mineral N inputs were considered. Losses of N in turnover were accounted for.

The model was successfully evaluated in several long-term and even in short-term field experiments [34,35,37].

### 2.7. Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) for a Latin square design using SAS® Studio 3.8. Data normality was tested using the Shapiro–Wilk test ($p < 0.05$). Tukey's honestly significance difference (HSD) was used as a post-hoc mean separation test ($p < 0.05$), where the ANOVA performed significant. N stocks of 2014, 2016, and 2017 were reciprocally transformed.

## 3. Results

### 3.1. Development of Soil Organic Matter and Nutrient Levels in the Soil

In the course of the experiment, we observed an oscillating development of both carbon nitrogen stocks in soils, which were more pronounced with C (Figure 1a,b). The highest C values were measured in 2012 and 2017, which was at the start and the end of the first regular crop rotation. With N, the highest values were measured in 2010 and 2016/2017. In 2014–2016, the treatments with additional application of plant-based compost (06M + BD and 06M + BD + K) showed significantly higher stocks of SOC as compared to treatments without compost application (06M and 06M + K). The application of plant-based compost also led to a significant differentiation in the soil N stocks between the treatments in 2011 and after 2016. Nevertheless, soil total N stocks decreased from 2009 to 2017 by 17.7% and 12% for 06M and 06M + K, respectively. The 06M + BD and 06M + BD + K treatments maintained the initial values.

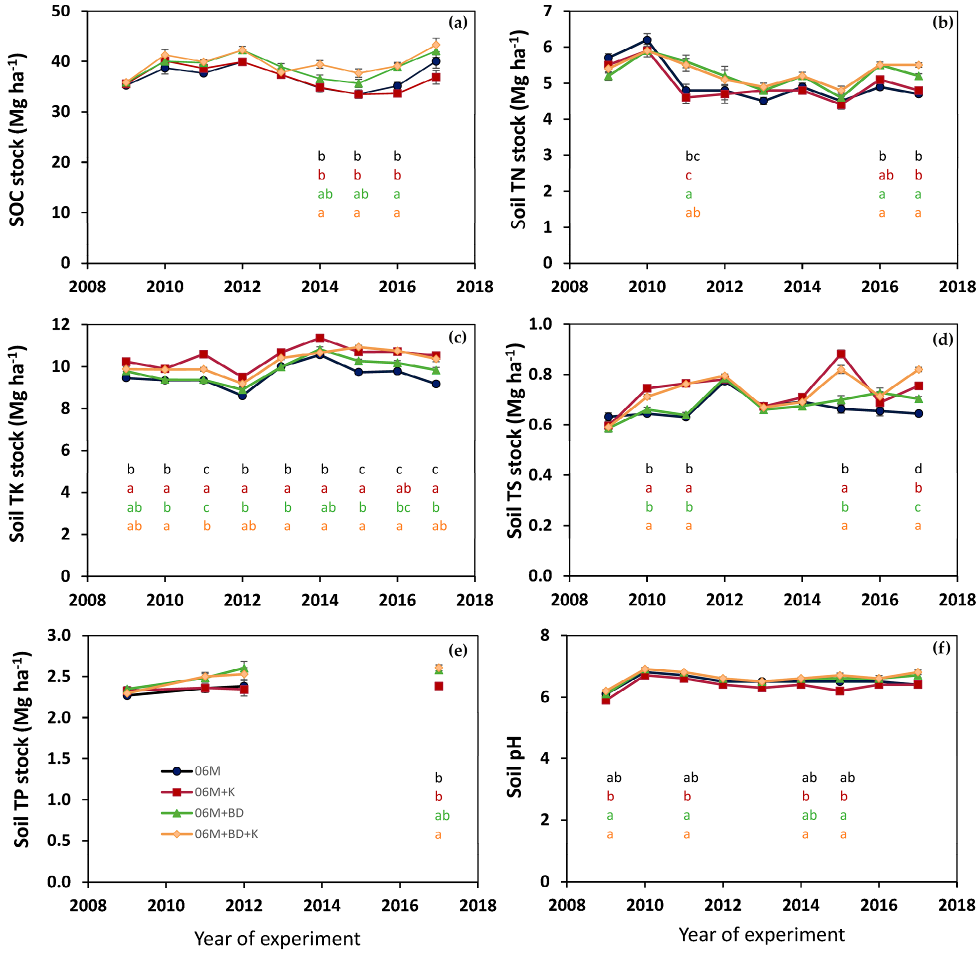


**Figure 1.** (**a**) Evolution of soil organic carbon stocks (Mg ha$^{-1}$), (**b**) soil total N stocks (Mg ha$^{-1}$), (**c**) soil total K stocks (Mg ha$^{-1}$), (**d**) soil total S stocks (Mg ha$^{-1}$), (**e**) soil total P stocks (Mg ha$^{-1}$), and soil pH (**f**) in the soil layer of 0–30 cm, over the period of 2009–2017, as affected by different fertilization treatments. Error bars represent the standard error of the mean value. Different letters within a year are significantly different at $p < 0.05$.

Potassium (K) stocks were also oscillating, but the pattern was different from that of C and N (Figure 1c). In 06M + K, the highest values were measured after the potassium sulfate fertilization events in 2011 and 2014 (cf. Table 2). In 06M + BD + K, however, these events could not be identified. As expected, potassium sulfate fertilization with and without compost application led to significantly higher soil total K stocks. As compared to

06M, all other treatments maintained or increased K stocks by 3% and 5% for 06M + K and 06M + BD + K, respectively.

Sulfur (S) stocks were higher in 06M + K and 06M + BD + K after potassium sulfate application in 2010, 2015, and 2017, but not in the other years with additional K and S fertilization in these treatments (Figure 1d). The highest increase in S stocks was observed for 06M + BD + K (+ 38.8%), followed by 06M + K (+ 26.5%) and 06M + BD (+ 20%).

Moreover, the 06M + BD + K treatment resulted in a significant increase in the soil total P stock (2.61 Mg $ha^{-1}$), as compared to the 06M (2.38 Mg $ha^{-1}$) and 06M+K (2.38 Mg $ha^{-1}$) treatments (Figure 1e), whereas 06M + BD were not significantly different from other treatments.

After 9 years, the soil pH in 06M, 06M + K, 06M + BD, and 06M + BD + K treatments were 0.3, 0.5, 0.6, and 0.4 units higher than the initial value in 2009 (Figure 1f). However, there were no statistically significant differences between the treatments in the last two years of the crop rotation.

### *3.2. Yields over the Crop Rotation 2012–2017*

Depending on the crop and the year of investigation, the results varied. However, the different fertilization influenced the annual marketable yields, as shown in Table 3.

**Table 3.** Yields (Mg $ha^{-1}$ dry matter), nitrogen yields (kg $ha^{-1}$ dry matter), soil nitrate–nitrogen (mg $kg^{-1}$ 0–90 cm) in spring of the rotation. Means followed by different letters within a row are significantly different at $p < 0.05$.

| | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|
| | **06M** | **06M + K** | **06M + BD** | **06M + BD + K** | **SEM** | **Pr > F** | **LSD** |
| **2012 clover grass** | | | | | | | |
| Yield Mg $ha^{-1}$ | 10.9 $^{b}$ | 11.9 $^{ab}$ | 11.3 $^{b}$ | 12.6 $^{a}$ | 0.26 | 0.0138 | 1.3 |
| N Yield kg $ha^{-1}$ | 306.0 $^{b}$ | 338.6 $^{ab}$ | 306.7 $^{b}$ | 352.7 $^{a}$ | 9.01 | 0.0237 | 44.1 |
| Soil $NO_3$–N mg $kg^{-1}$ | 5.48 | 5.55 | 6.05 | 5.85 | 0.56 | 0.8739 | 2.7 |
| **2013 clover grass** | | | | | | | |
| Yield Mg $ha^{-1}$ | 7.7 | 8.5 | 7.5 | 8 | 0.32 | 0.2386 | 1.5 |
| N Yield kg $ha^{-1}$ | 172.6 | 198.6 | 164.2 | 175.1 | 8.61 | 0.1218 | 42.2 |
| Soil $NO_3$–N mg $kg^{-1}$ | 10.63 | 12.1 | 11.3 | 12.2 | 0.55 | 0.245 | 2.7 |
| **2014 winter wheat** | | | | | | | |
| Yield Mg $ha^{-1}$ | 2.5 $^{b}$ | 3.0 $^{a}$ | 2.8 $^{ab}$ | 3.1 $^{a}$ | 0.09 | 0.0121 | 0.4 |
| N Yield kg $ha^{-1}$ | 47.2 $^{b}$ | 56.8 $^{ab}$ | 52.8 $^{ab}$ | 58.1 $^{a}$ | 1.98 | 0.0297 | 9.7 |
| Soil $NO_3$–N mg $kg^{-1}$ | 12.28 | 14.05 | 12.6 | 12.1 | 0.53 | 0.1296 | 2.6 |
| **2015 fodder maize** | | | | | | | |
| Yield Mg $ha^{-1}$ | 10.8 $^{b}$ | 11.9 $^{ab}$ | 12.2 $^{ab}$ | 12.8 $^{a}$ | 0.33 | 0.0244 | 1.6 |
| N Yield kg $ha^{-1}$ | 164.1 $^{b}$ | 180.7 $^{ab}$ | 184.2 $^{ab}$ | 201.4 $^{a}$ | 5.42 | 0.0164 | 26.5 |
| Soil $NO_3$–N mg $kg^{-1}$ | 19.95 | 21.78 | 20.48 | 21.58 | 0.5 | 0.1117 | 2.4 |
| **2016 red beet** | | | | | | | |
| Yield Mg $ha^{-1}$ | 5.7 $^{ab}$ | 5.5 $^{b}$ | 6.2 $^{a}$ | 6.1 $^{ab}$ | 0.09 | 0.0339 | 0.7 |
| N Yield kg $ha^{-1}$ | 91.7 $^{c}$ | 86.4 $^{c}$ | 97.8 $^{ab}$ | 102.53 $^{a}$ | 1.66 | 0.0021 | 8.1 |
| Soil $NO_3$–N mg $kg^{-1}$ | 23.43 | 24.15 | 23.95 | 23.73 | 0.94 | 0.952 | 4.6 |
| **2017 spring wheat** | | | | | | | |
| Yield Mg $ha^{-1}$ | 2.4 $^{b}$ | 2.5 $^{b}$ | 2.9 $^{a}$ | 3.0 $^{a}$ | 0.08 | 0.0051 | 0.4 |
| N Yield kg $ha^{-1}$ | 42.3 $^{b}$ | 43.7 $^{b}$ | 54.9 $^{a}$ | 56.5 $^{a}$ | 1.64 | 0.0015 | 8 |
| Soil $NO_3$–N mg $kg^{-1}$ | 18.1 | 17.43 | 19.73 | 19 | 0.52 | 0.0775 | 2.5 |

Abbreviations: SEM, standard error of the mean value; and LSD, Least Significant Difference.

The yields differed significantly in 2012, 2014, 2016, and 2017, between 06M and 06M + BD + K. Further, the application of compost plus potassium sulfate resulted in higher N yields of all treatments, as compared to 06M in all years, except for 2013. Despite the different N input, the mineral N in spring was similar in all treatments.

Fertilization resulted in significant marketable yield increases cumulated over the 6-year crop rotation, which followed the order—06M < 06M + K < 06M + BD < 06M + BD + K (Figure 2a). The significantly highest marketable yields cumulated over the 6-year crop rotation was achieved with the addition of plant-based compost, with and without potassium sulfate (26.1 Mg ha$^{-1}$ and 25.4 Mg ha$^{-1}$, respectively), while the treatment with only deep litter (06M) achieved 22.7 Mg ha$^{-1}$, which were 13% and 10.6% less than 06M + BD + K and 06M + BD.

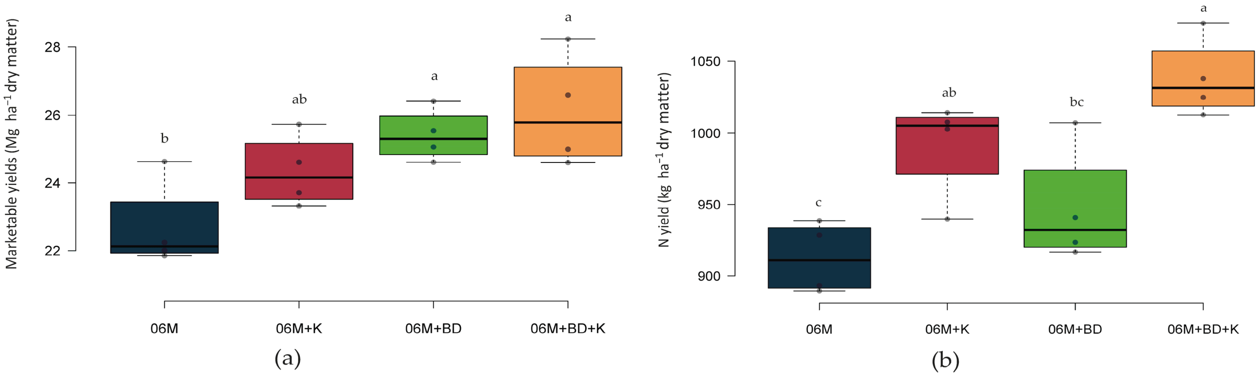


**Figure 2.** (**a**) Marketable yields (Mg ha$^{-1}$ dry matter) included winter wheat, maize, red beet, and spring wheat. (**b**) Total nitrogen yields (kg ha$^{-1}$ dry matter) included clover grass, winter wheat (grain and straw), maize, red beet (root and side product), and spring wheat (grain and straw). Results are cumulated over the 6-year crop rotation, boxplots with different letters are significantly different at $p < 0.05$.

Fertilization with potassium sulfate significantly influenced the total aboveground biomass N uptake over the crop rotation, being significantly higher in 06M + K and 06M + BD + K than in 06M (Figure 2b). Compost application (06M + BD) did not increase the N yield as compared to 06M and 06M + K, but was significantly lower than the combination of compost and potassium sulfate.

### *3.3. Nutrient Balance over the Crop Rotation*

Nutrient inputs in the treatments varied according to the fertilization regimes, and the exports varied according to the yield levels. The N:P:K:S ratios were only different between treatments on the input side, but not for the nutrient exports.

Balances of all nutrients under study were negative with the 06M treatment (Table 4). Inputs did not compensate for nutrient export in this treatment.

**Table 4.** Mean total nitrogen (N), sulfur (S), potassium (K) and phosphorus (P) balance across one crop rotation (2012–2017) in kg ha$^{-1}$ year$^{-1}$.

| | | **N Balance** | | | **S Balance** | |
|---|---|---|---|---|---|---|
| **Treatments** | **Input kg ha$^{-1}$ year$^{-1}$** | **Export kg ha$^{-1}$ year$^{-1}$** | **Budget kg ha$^{-1}$ year$^{-1}$** | **Input kg ha$^{-1}$ year$^{-1}$** | **Export kg ha$^{-1}$ year$^{-1}$** | **Budget kg ha$^{-1}$ year$^{-1}$** |
| 06M | 149 | 152 | −3 | 3 | 12 | −8 |
| 06M + K | 160 | 165 | −5 | 68 | 14 | 54 |
| 06M + BD | 220 | 158 | 62 | 17 | 12 | 5 |
| 06M + BD + K | 232 | 173 | 59 | 55 | 14 | 40 |
| | | **K Balance** | | | **P Balance** | |
| 06M | 39 | 113 | −74 | 7 | 24 | −17 |
| 06M + K | 189 | 164 | 25 | 7 | 25 | −17 |
| 06M + BD | 162 | 127 | 35 | 37 | 26 | 11 |
| 06M + BD + K | 249 | 169 | 80 | 37 | 27 | 10 |

Potassium sulfate application turned the K and S balances positive in the 06M + K treatment, while the P and N budgets became positive only with compost application in the experiment (treatments 06M + BD and 06M + BD + K).

### 3.4. Soil Organic Matter Balances and Modeling

The good correlation between observed and predicted C and N development (Figure 3) indicated that assumptions in the model seemed to be more or less applicable at the site, even though the undulating development of SOC was not captured in that magnitude by the model.

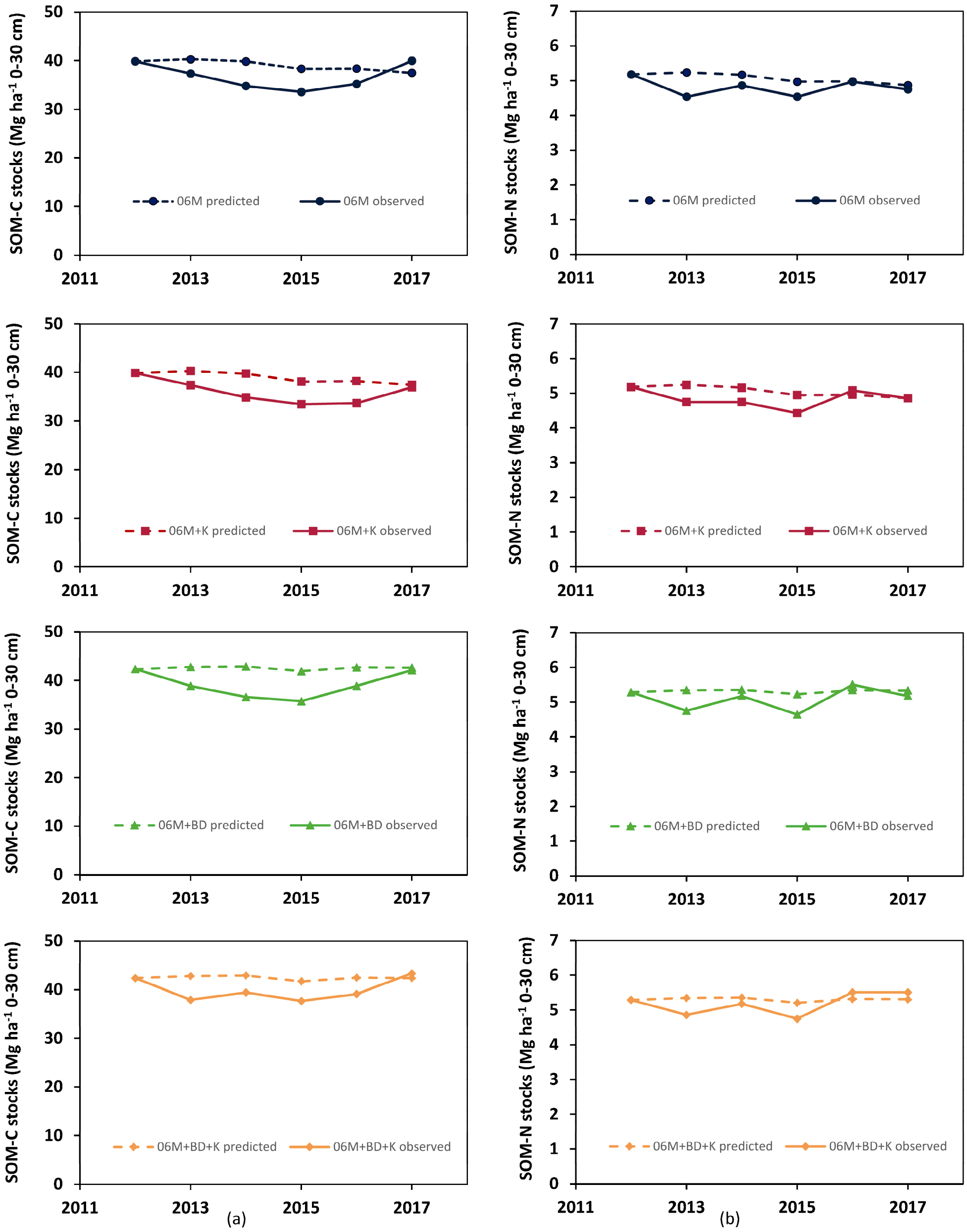


**Figure 3.** Observed and predicted development of soil organic C (**a**) and N (**b**) under the rotational cycle 2012–2017 in the long-term field experiment. Predicted values were calculated with the HU-MOD model.

According to the coupled C- and N-based soil organic matter balance, the supply of organic matter was too low in the 06M and 06M + K treatments to compensate for mineralization (Table 5). With compost application in 06M + BD and 06M + BD + K, the balance became slightly positive, but there was not much potential for increasing yields.

Modeling opportunities to improve organic matter supply to soils in treatments with and without compost (Table 6), we found that the inclusion of non-legume catch crops would marginally improve SOM balances, but the budgets would almost not change in

06M. An optimization of the crop rotation (substitution of fodder maize by oats and new crop order) would significantly improve the SOM budget, but still the balance of the 06M treatment would stay negative. In the compost treatments, the same optimization of the crop rotation would allow for a 50% reduction of compost application, without significantly changing the budget (Table 7).

**Table 5.** Coupled C- and N-based soil organic matter balance with HU-MOD across one crop rotation (2012–2017) in kg ha$^{-1}$ year$^{-1}$.

| | **06M** | | **06M + K** | | **06M + BD** | | **06M + BD + K** | |
|---|---|---|---|---|---|---|---|---|
| Crop Rotation | SOM-C kg ha$^{-1}$ year$^{-1}$ | SOM-N kg ha$^{-1}$ year$^{-1}$ | SOM-C kg ha$^{-1}$ year$^{-1}$ | SOM-N kg ha$^{-1}$ year$^{-1}$ | SOM-C kg ha$^{-1}$ year$^{-1}$ | SOM-N kg ha$^{-1}$ year$^{-1}$ | SOM-C kg ha$^{-1}$ year$^{-1}$ | SOM-N kg ha$^{-1}$ year$^{-1}$ |
| clover grass | 290.4 | 37.8 | 354.6 | 46.1 | 356.7 | 44.6 | 411.5 | 51.4 |
| clover grass | 427.3 | 51.9 | 445.7 | 56.7 | 436.2 | 53.3 | 439.0 | 56.3 |
| winter wheat | −453.7 | −63.4 | −555.8 | −75.7 | 126.8 | 18.0 | 101.6 | 13.4 |
| fodder maize | −1190.4 | −160.9 | −1345.0 | −177.9 | −692.8 | −90.0 | −882.7 | −111.3 |
| red beet | 38.1 | 5.4 | 91.5 | 13.8 | 814.0 | 115.3 | 750.8 | 105.7 |
| spring wheat | −541.2 | −64.4 | −480.5 | −63.2 | 266.5 | 32.8 | 238.3 | 30.3 |
| crop rotation | −238.3 | −32.3 | −248.3 | −33.4 | 217.9 | 29.0 | 176.4 | 24.3 |

**Table 6.** Scenarios for optimized crop rotation for treatment by 06M. Coupled C- and N-based soil organic matter balance with HU-MOD across one crop rotation (2012–2017) in kg ha$^{-1}$ year$^{-1}$. For the scenarios, the CN reference was standardized, therefore, the budgets of the original scenarios differed from those in Table 5.

| | **06M Original** | | **06M + Catch Crops** | | | **06M Optimized** | |
|---|---|---|---|---|---|---|---|
| Crop Rotation | SOM-C kg ha$^{-1}$ year$^{-1}$ | SOM-N kg ha$^{-1}$ year$^{-1}$ | SOM-C kg ha$^{-1}$ year$^{-1}$ | SOM-N kg ha$^{-1}$ year$^{-1}$ | Crop rotation | SOM-C kg ha$^{-1}$ year$^{-1}$ | SOM-N kg ha$^{-1}$ year$^{-1}$ |
| clover grass | 302.1 | 37.8 | 302.1 | 37.8 | clover grass | 396.3 | 49.5 |
| clover grass | 414.9 | 51.9 | 414.9 | 51.9 | clover grass | 234.5 | 29.3 |
| winter wheat | −507.0 | −63.4 | −507.0 | −63.4 | oats | −388.7 | −48.6 |
| catch crop # | no | no | oil radish # | | catch crop # | oil radish # | |
| fodder maize | −1287.0 | −160.9 | −1251.7 | −156.5 | red beet * | 552.5 | 69.1 |
| red beet * | 43.0 | 5.4 | 43.0 | 5.4 | winter wheat | −497.2 | −62.2 |
| catch crop # | no | no | phacelia # | | catch crop # | phacelia # | |
| spring wheat | −514.8 | −64.4 | −459.1 | −57.4 | spring wheat | −508.9 | −63.6 |
| underseed | no | no | clover grass | | underseed | clover grass | |
| crop rotation | −258.1 | −32.3 | −243.0 | 37.8 | crop rotation | −35.2 | −4.4 |

* Fertilization: 35 Mg ha$^{-1}$ with farmyard manure # Catch crop effect is considered in the balance value of the main crop.

**Table 7.** Scenario for the optimized crop rotation for treatment by 06M + BD + K. Coupled C- and N-based soil organic matter balance with the HU-MOD across one crop rotation (2012–2017) in kg ha$^{-1}$ year$^{-1}$. For the scenario, the CN reference was standardized, therefore, the budgets of the original scenario differed from those in Table 5.

| | **06M + BD + K Original** | | |
|---|---|---|---|
| **Crop Rotation** | **Fertilization** | **SOM-C kg ha$^{-1}$ year$^{-1}$** | **SOM-N kg ha$^{-1}$ year$^{-1}$** |
| clover grass | | 411.5 | 51.4 |
| clover grass | | 450.3 | 56.3 |
| winter wheat | compost 30 Mg ha$^{-1}$ | 106.9 | 13.4 |
| fodder maize | compost 30 Mg ha$^{-1}$ | −890.4 | −111.3 |
| red beet | FYM * 35 Mg ha$^{-1}$ + compost 30 Mg ha$^{-1}$ | 846 | 105.7 |
| spring wheat | compost 30 Mg ha$^{-1}$ | 242.5 | 30.3 |
| crop rotation | | 194.5 | 24.3 |
| | **06M + BD + K optimized (compost reduced by 50%)** | | |
| clover grass | | 411.5 | 51.4 |
| clover grass | | 450.3 | 56.3 |
| oats | compost 30 Mg ha$^{-1}$ | 207.2 | 25.9 |
| catch crop | | oil radish # | |
| red beet | FYM * 35 Mg ha$^{-1}$ | 499.6 | 62.4 |
| winter wheat | | −566.8 | −70.9 |
| catch crop | | Phacelia # | |
| spring wheat | compost 30 Mg ha$^{-1}$ | 296.8 | 37.1 |
| crop rotation | | 216.4 | 27.1 |

* FYM = farmyard manure; # Catch crop effect is considered in the balance value of the main crop.

## 4. Discussion

### *4.1. Soil Organic Matter and Nutrients*

The development of soil organic matter is a rather slow process, and it will likely take more than a 6-year crop rotation or even an 8-year observation period, until significant treatment effects emerge [38]. However, we can already observe some differentiation in this initial phase of the field experiment. As could be expected, both C and N values were higher in the compost treatments than in the other two treatments. Further, it appears that decreasing C and N stocks in the treatments without compost application could indicate an insufficient supply of organic matter to soils. However, since the turnover of organic matter in soils is not only dependent on actual management, but also on site conditions and management history [36,39,40], it is not possible to determine whether farmyard manure application corresponding to a stocking rate of 0.6 LU cattle $ha^{-1}$ is insufficient in general, or only worked under the specific conditions of this experiment.

Unfortunately, there are almost no studies on the stocking rate and the corresponding available manure effects on soil fertility in the scientific literature today. In the well-known DOK experiments in Switzerland, farmyard manure was applied at rates corresponding to 0.7 and 1.4 LU cattle per ha, but soil carbon stocks decreased under all treatments in the experiment, except for a biodynamic treatment with composted manure application, corresponding to 1.4 LU $ha^{-1}$ [41]. This was most likely an effect of the site history. Leithold et al. [3] assumed that 1 LU $ha^{-1}$ would be an adequate stocking rate to maintain soil fertility in productive organic farming systems. Nevertheless, Schulz et al. [4] observed even increasing SOM levels in the Organic Arable Farming Experiment Gladbacherhof (Germany) at the FYM application, corresponding to 1 LU cattle per ha.

Soil organic matter balances provide some explanation for the observed trends of soil C and N, despite the uncertainties in the parametrization (see below). According to the model calculations, organic matter supply is not sufficient in the treatments without compost application to compensate for turnover losses, despite the low yield level. It was considered that the N uptake of crops is taken as a proxy for soil organic matter mineralization in the model [34]. The yield level of non-legume crops is, therefore, positively correlated with the demand for organic matter to compensate for SOM mineralization [42]. At present, only treatments with compost applications have the potential to build up SOM. However, the demand for organic matter would increase if the yield levels shall be improved in the experiment.

The development of K, S, and P stocks reflects the different input rates in the treatments. Therefore, treatments with compost application (06M + BD, 06M + BD + K) have higher p-values than the two other treatments, and treatments with potassium sulfate application (06M + K, 06M + BD + K) have higher K and S values.

### *4.2. Crop Yields*

The fodder legumes obviously benefitted from potassium sulfate application. From our results we might not conclude whether this was a K- or S-effect. Both elements play a vital role in biological nitrogen fixation, and the effect of variable availability is similar [17]. Usually, K is not a limiting factor in arable soils in Germany. At the site of the field experiment, however, K supply might be limited by K fixation.

Row crops (maize and red beet) both benefitted from compost application, while K/S fertilization had a smaller effect. Here, it must be considered that all treatments received farmyard manure. According to Blake et al. [43], farmyard manure application is more effective in supplying crops with K than mineral fertilizers. Lehtinen et al. [10] found that K input with manure-based compost was higher than with plant-based compost. In fact, we found that K use efficiency was highest in the 06M treatment and lowest in the 06M + BD + K.

The reaction of the cereals to fertilization was not consistent. Higher winter wheat yields in the treatments with K fertilization are likely an effect of the preceding fodder legumes. Spring wheat at the end of the crop rotation on the other hand obviously profited from compost fertilization.

Altogether, yield levels were comparably low in the experiment. Nutrient balances revealed that the actual nutrient supply did not offer much potential for yield increases, if at all. Increasing yields would require additional efforts in soil fertility management, like the use of green manure and catch crops to improve N supply [44], and additional fertilization.

### *4.3. Nutrient and Soil Organic Matter Balances*

Nutrient balances were negative for both S, P, and K in the control treatment (06M). This corresponded to the results of Berry et al. [45], which indicate negative K and P balances in organic farming systems without external inputs. In our field experiment, the application of compost compensated for nutrient exports (and losses), even in the treatment without additional Potassium sulfate fertilization. The utilization of additional internal organic matter resources, therefore, is a good opportunity to improve nutrient balances on arable land, but of course this measure did not close the nutrient cycle on the farm level. Instead, nutrients were transferred and re-distributed within the farm. Reimer et al. [46] addressed this situation in their meta-analysis of nutrient budgets in organic farms in Germany. The authors emphasized that positive nutrient balances at the farm gate could not be achieved without nutrient imports. In principle, biowaste compost and sewage sludge would be the appropriate sources to close nutrient cycles. However, both sources featured the risk to import mineral and organic pollutants into organic farming systems [47]. Therefore, the utilization of internal resources must be considered a viable interim option.

Soil organic matter balances were calculated with the HU-MOD model [34,35]. The tool was originally developed for decision support in farming practice, but unlike most other so-called 'Humus balance methods' it could also be used for analytical purposes [36].

The advantage of the HU-MOD model was that the utilization of N in plant biomass as a proxy for the mineralization of soil organic matter allowed us to by-pass the need for information on site factors, as it was assumed that their effect on soil organic matter mineralization became visible in the N fluxes that were considered in the model. However, the procedure made the model susceptible to errors resulting from erroneous estimates of N pools. Most importantly, biological nitrogen fixation is known to be highly variable [48], even though [49] found that there is a statistically significant average rate of approximately 0.7 kg BNF-N per kg plant shoot N. Nevertheless, the error of this average was high enough to severely impact site-specific N balance calculations. As we did not measure BNF, we could not account for any differentiation between the treatments in N yield from this process.

Regarding the congruence between the observed and predicted trends of soil C and N stocks, it must be considered that the model output does refers to the total rooted soil layer. A comparison with topsoil C and N trends, therefore, comprises the risk that C and N changes in deeper soil layers are not captured. Soil organic matter in the subsoil is usually more stable than topsoil SOM [50], and turnover mainly takes place in the topsoil. However, it was argued that organic matter turnover in subsoil is relevant for the calculation of actual C balances [51]. Therefore, it cannot be concluded whether the deviations between measured topsoil organic matter changes and the calculated changes according to the HU-MOD model indicate parametrization errors, or are caused by the limited database on C and N changes in the soil.

### *4.4. Practical Implications*

#### 4.4.1. Farm Compost to Open Additional Organic Matter Sources

In our experiment, we used on-farm composting as an option to increase organic matter supply to soils based on own resources of a farm. This compost provided an additional input of several nutrients. Besides N, the compost contained considerable amounts of P, K, and even S and could be considered an effective 'full-fertilizer' with a low leaching potential [52]. Compost application therefore could effectively increase crop yields [11,13,53].

As outlined by D'Hose et al. [53], the positive effect of farm compost on crop yields should not only be ascribed to the additional nutrient input, but also to the improvement of growing conditions for the crops. Compost application improves soil physical properties [52,54], and has a beneficial effect of compost on pathogen regulation in soils and plant health [54–56]. Further, compost might even facilitate the formation of arbuscular mycorrhizas [57].

It is widely acknowledged that compost builds up soil organic matter [8,10,52,58]. This improves microbial activity and related ecosystem services [59]. For example, organic matter build-up improves the accessibility of micronutrients to plants [14]. In general, there is a positive relationship between soil organic matter and crop yields [15,42].

Composting was also identified as a viable option to reduce ecological trade-offs between soil fertility management and environment and climate protection [60,61].

### 4.4.2. Optimization

Modeling possible adaptations of crop rotation or fertilization in selected treatments indicated a low potential of catch crops to improve the SOM balance. This is supported by findings of White et al. [58] as well as Tautges et al. [12]. However, it contradicts the results of Poeplau and Don [62] who concluded that the introduction of catch crops into crop rotations would have a considerable effect on carbon sequestration in Germany. The reason for the different observations could be a stoichiometric effect, were N availability limits C retention from catch crops in the soil [63]. As the C:N ratio of organic material is narrowed down in the turnover process, excess C is lost by respiration [64]. At the same time, it should be considered that increasing N supply causes a priming effect [65], which pushes organic matter turnover. The impact of catch crops on soil organic matter is therefore probably dependent on both C and N amounts and availability, alongside with biological and physical factors. As we included non-legume catch crops in the model that did not receive any fertilization, the model calculated only slightly positive balances based on the fertilization effect of the catch crops on the succeeding crops. However, it should be considered that soil N taken up by the catch crops might have leached in a corresponding bare fallow period. On the other hand, N leaching usually is very low under the N-limited conditions of organic farming [66], especially on heavy soils.

In contrast, the substitution of fodder maize by oats proved a very effective measure in the modeling study, as this adaptation significantly decreased N export and the related demand for organic matter. Field experiments comparing maize and cereal cultivation effects on soil organic matter are rare. Nevertheless, in a study from Poland, Rychcik et al. [67] found that maize and grain legumes had lower soil carbon values than cereals. In a recent paper, Benbi et al. [68] showed that soil C respiration was three-fold higher under maize, as compared to wheat. Our results therefore are plausible.

Of course, changes in the crop rotation need to be discussed against the background of the requirements in the farming system. A substitution of fodder maize by cereals might not always fit to the specific situation. In such cases, intercropping could provide an option to improve the soil organic matter balance of maize [69].

## 5. Conclusions

Sustainable nutrient supply might be threatened in organic farming systems with a stocking rate of 0.6 LU cattle per hectare, if fertilization only relies on the available manure. Additional compost application provides a solution, as compost provides a direct additional input of nutrients, and contributes to the nutrition of legumes, which in turn enhances biological N fixation. Additional supply of essential nutrients (K, S) does further improve BNF. This compost can be made from internal resources on the farm (e.g., hedge-cutting), to be independent from external inputs and to avoid the import of pollutants.

However, it must be considered that own farm compost makes new nutrient, and the organic matter sources available on the farm and is a viable interim solution, but does not solve the problem of open nutrient cycles at the farm gate level.

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## References

1. Fageria, N.K. Role of Soil Organic Matter in Maintaining Sustainability of Cropping Systems. *Commun. Soil Sci. Plant Anal.* **2012**, *43*, 2063–2113. [CrossRef]
2. Gattinger, A.; Muller, A.; Haeni, M.; Skinner, C.; Fliessbach, A.; Buchmann, N.; Mäder, P.; Stolze, M.; Smith, P.; Scialabba, N.E.-H.; et al. Enhanced top soil carbon stocks under organic farming. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 18226–18231. [CrossRef] [PubMed]
3. Leithold, G.; Hülsbergen, K.-J.; Brock, C. Organic matter returns to soils must be higher under organic compared to conventional farming. *J. Plant Nutr. Soil Sci.* **2014**, *178*, 4–12. [CrossRef]
4. Schulz, F.; Brock, C.; Schmidt, H.; Franz, K.-P.; Leithold, G. Development of soil organic matter stocks under different farm types and tillage systems in the Organic Arable Farming Experiment Gladbacherhof. *Arch. Agron. Soil Sci.* **2013**, *60*, 313–326. [CrossRef]
5. Brock, C.; Oberholzer, H.-R.; Schwarz, J.; Fließbach, A.; Hülsbergen, K.-J.; Koch, W.; Pallutt, B.; Reinicke, F.; Leithold, G.; Fliessbach, A. Soil organic matter balances in organic versus conventional farming—modelling in field experiments and regional upscaling for cropland in Germany. *Org. Agric.* **2012**, *2*, 185–195. [CrossRef]
6. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176. [CrossRef]
7. Amanullah; Khalid, S.; Imran; Khan, H.A.; Arif, M.; Altawaha, A.R.; Adnan, M.; Fahad, S.; Parmar, B. Organic Matter Management in Cereals Based System: Symbiosis for Improving Crop Productivity and Soil Health. *Sustain. Agric. Rev.* **2019**, *29*, 67–92. [CrossRef]
8. Martínez-Blanco, J.; Lazcano, C.; Christensen, T.H.; Muñoz, P.; Rieradevall, J.; Møller, J.; Antón, A.; Boldrin, A. Compost benefits for agriculture evaluated by life cycle assessment. A review. *Agron. Sustain. Dev.* **2013**, *33*, 721–732. [CrossRef]
9. Azim, K.; Soudi, B.; Boukhari, S.; Perissol, C.; Roussos, S.; Alami, I.T. Composting parameters and compost quality: A literature review. *Org. Agric.* **2018**, *8*, 141–158. [CrossRef]
10. Lehtinen, T.; Dersch, G.; Söllinger, J.; Baumgarten, A.; Schlatter, N.; Aichberger, K.; Spiegel, H. Long-term amendment of four different compost types on a loamy silt Cambisol: Impact on soil organic matter, nutrients and yields. *Arch. Agron. Soil Sci.* **2016**, *63*, 663–673. [CrossRef]
11. Kurzemann, F.; Plieger, U.; Probst, M.; Spiegel, H.; Sandén, T.; Ros, M.; Insam, H. Long-Term Fertilization Affects Soil Microbiota, Improves Yield and Benefits Soil. *Agronomy* **2020**, *10*, 1664. [CrossRef]
12. Tautges, N.E.; Chiartas, J.L.; Gaudin, A.C.M.; O'Geen, A.T.; Herrera, I.; Scow, K.M. Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. *Glob. Chang. Biol.* **2019**, *25*, 3753–3766. [CrossRef] [PubMed]
13. Wortman, S.E.; Holmes, A.A.; Miernicki, E.; Knoche, K.; Pittelkow, C.M. First-Season Crop Yield Response to Organic Soil Amendments: A Meta-Analysis. *Agron. J.* **2017**, *109*, 1210–1217. [CrossRef]

14. Dhaliwal, S.; Naresh, R.; Mandal, A.; Singh, R.; Dhaliwal, M. Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: A review. *Environ. Sustain. Indic.* **2019**, *1–2*, 100007. [CrossRef]
15. Oldfield, E.E.; Bradford, M.A.; Wood, S.A. Global meta-analysis of the relationship between soil organic matter and crop yields. *Soil* **2019**, *5*, 15–32. [CrossRef]
16. Vance, C.P.; Graham, P.H.; Allan, D.L. Biological Nitrogen Fixation: Phosphorus–A Critical Future Need? In *Proceedings of the Nitrogen Fixation: From Molecules to Crop Productivity*; Springer: Berlin, Germany, 2005; Volume 12, pp. 509–514.
17. Divito, G.A.; Sadras, V.O. How do phosphorus, potassium and sulphur affect plant growth and biological nitrogen fixation in crop and pasture legumes? A meta-analysis. *Field Crops Res.* **2014**, *156*, 161–171. [CrossRef]
18. Israel, D.W. Investigation of the Role of Phosphorus in Symbiotic Dinitrogen Fixation. *Plant Physiol.* **1987**, *84*, 835–840. [CrossRef] [PubMed]
19. Sulieman, S.; Van Ha, C.; Schulze, J.; Tran, L.-S.P. Growth and nodulation of symbiotic Medicago truncatula at different levels of phosphorus availability. *J. Exp. Bot.* **2013**, *64*, 2701–2712. [CrossRef]
20. Almeida, J.; Hartwig, U.A.; Frehner, M.; Nösberger, J.; Lüscher, A. Evidence that P deficiency induces N feedback regulation of symbiotic $N_2$ fixation in white clover (*Trifolium repens* L.). *J. Exp. Bot.* **2000**, *51*, 1289–1297. [CrossRef]
21. Høgh-Jensen, H. The effect of potassium deficiency on growth and $N_2$-fixation in Trifolium repens. *Physiol. Plant.* **2003**, *119*, 440–449. [CrossRef]
22. Lea, P.J.; Sodek, L.; Parry, M.A.J.; Shewry, P.R.; Halford, N.G. Asparagine in plants. *Ann. Appl. Biol.* **2007**, *150*, 1–26. [CrossRef]
23. FAO. World reference base for soil resources 2014 International soil classification system for naming soils and creating legends for soil maps. *World Soil Resour. Rep.* **2015**, *106*, 162–163.
24. Steiner, R. *Geisteswissenschaftliche Grundlagen zum Gedeihen der Landwirtschaft: Landwirtschaftlicher Kurs. Koberwitz bei Breslau 1924, und ein Vortrag, Dornach 1924*; Schwabe: Karlsruhe, Germany, 2015; ISBN 3727485124.
25. van Eimern, J.; Häckel, H. *Wetter und Klimakunde. Für Landwirte, Gärtner, Winzer und Landschaftspfleger: Ein Lehrbuch der Agrarmeteorologie*; Eugen Ulmer Verlag: Stuttgart, Germany, 1979; pp. 50–51.
26. ISO 13878. *Soil Quality Determination of Total Nitrogen Content by Dry Combustion ("Elemental Analysis")*; International Organization for Standardization: Geneva, Switzerland, 1998.
27. DIN EN 16168. *Sludge, Treated Biowaste and Soil–Determination of Total Nitrogen–Dry Combustion Method*; Deutsches Institut für Normung e.V.: Berlin, Germany, 2012. [CrossRef]
28. ISO 11885. *Water Quality—Determination of Selected Elements by Inductively Coupled Plasma Optical Emission Spectrometry*; International Organization for Standardization: Geneva, Switzerland, 2009. [CrossRef]
29. Hoffmann, G. *Methodenbuch Band 1, Die Untersuchung von Böden*; VDLUFA: Darmstadt, Germany, 1991.
30. DIN 19682-10. *Methods of Soil Investigations for Agricultural Water Engineering–Field Tests–Part 10: Description and Evaluation of Soil Structure*; Deutsches Institut für Normung e.V.: Berlin, Germany, 2007. [CrossRef]
31. Naumann, C.; Bassler, R.; Seibold, R.; Barth, K. *VDLUFA-Methodenbuch Band III, Die Chemische Untersuchung von Futtermitteln*; VDLUFA: Darmstadt, Germany, 1997.
32. ISO 12099. *Animal Feeding Stuffs, Cereals and Milled Cereal Products*; International Organization for Standardization: Geneva, Switzerland, 2017. [CrossRef]
33. Stein-Bachinger, K.; Bachinger, J. *Nährstoffmanagement im ökologischen Landbau: Ein Handbuch für Beratung und Praxis; Berechnungsgrundlagen, Faustzahlen, Schätzverfahren zur Erstellung von Nährstoffbilanzen; Handlungsempfehlungen zum Effizienten Umgang mit Innerbetrieblichen Nährstoffressourcen, Insbesondere Stickstoff*; Landwirtschaftsverlag: Münster, Germany, 2004; ISBN 3784321682.
34. Brock, C.; Hoyer, U.; Leithold, G.; Hülsbergen, K.-J. The humus balance model (HU-MOD): A simple tool for the assessment of management change impact on soil organic matter levels in arable soils. *Nutr. Cycl. Agroecosystems* **2012**, *92*, 239–254. [CrossRef]
35. Knebl, L.; Leithold, G.; Brock, C. Improving minimum detectable differences in the assessment of soil organic matter change in short-term field experiments. *J. Plant Nutr. Soil Sci.* **2015**, *178*, 35–42. [CrossRef]
36. Brock, C.; Franko, U.; Oberholzer, H.-R.; Kuka, K.; Leithold, G.; Kolbe, H.; Reinhold, J. Humus balancing in Central Europe-concepts, state of the art, and further challenges. *J. Plant Nutr. Soil Sci.* **2013**, *176*, 3–11. [CrossRef]
37. Knebl, L.; Leithold, G.; Schulz, F.; Brock, C. The role of soil depth in the evaluation of management-induced effects on soil organic matter. *Eur. J. Soil Sci.* **2017**, *68*, 979–987. [CrossRef]
38. Smith, P. How long before a change in soil organic carbon can be detected? *Glob. Chang. Biol.* **2004**, *10*, 1878–1883. [CrossRef]
39. Stockmann, U.; Adams, M.; Crawford, J.W.; Field, D.J.; Henakaarchchi, N.; Jenkins, M.; Minasny, B.; McBratney, A.B.; Courcelles, V.D.R.D.; Singh, K.; et al. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agric. Ecosyst. Environ.* **2013**, *164*, 80–99. [CrossRef]
40. Crews, T.E.; Rumsey, B.E. What Agriculture Can Learn from Native Ecosystems in Building Soil Organic Matter: A Review. *Sustainability* **2017**, *9*, 578. [CrossRef]
41. Fließbach, A.; Oberholzer, H.-R.; Gunst, L.; Mäder, P. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. *Agric. Ecosyst. Environ.* **2007**, *118*, 273–284. [CrossRef]
42. Brock, C.; Fließbach, A.; Oberholzer, H.-R.; Schulz, F.; Wiesinger, K.; Reinicke, F.; Koch, W.; Pallutt, B.; Dittman, B.; Zimmer, J.; et al. Relation between soil organic matter and yield levels of nonlegume crops in organic and conventional farming systems. *J. Plant Nutr. Soil Sci.* **2011**, *174*, 568–575. [CrossRef]

43. Blake, L.; Mercik, S.; Koerschens, M.; Goulding, K.; Stempen, S.; Weigel, A.; Poulton, P.; Powlson, D. Potassium content in soil, uptake in plants and the potassium balance in three European long-term field experiments. *Plant Soil* **1999**, *216*, 1–14. [CrossRef]
44. Thorup-Kristensen, K.; Dresbøll, D.B.; Kristensen, H.L. Crop yield, root growth, and nutrient dynamics in a conventional and three organic cropping systems with different levels of external inputs and N re-cycling through fertility building crops. *Eur. J. Agron.* **2012**, *37*, 66–82. [CrossRef]
45. Berry, P.M.; Sylvester-Bradley, R.; Philipps, L.; Hatch, D.J.; Cuttle, S.P.; Rayns, F.W.; Gosling, P. Is the productivity of organic farms restricted by the supply of available nitrogen? *Soil Use Manag.* **2006**, *18*, 248–255. [CrossRef]
46. Reimer, M.; Möller, K.; Hartmann, T.E. Meta-analysis of nutrient budgets in organic farms across Europe. *Org. Agric.* **2020**, *10*, 65–77. [CrossRef]
47. Alvarenga, P.; Mourinha, C.; Farto, M.; Santos, T.; Palma, P.; Sengo, J.; Morais, M.-C.; Cunha-Queda, C. Sewage sludge, compost and other representative organic wastes as agricultural soil amendments: Benefits versus limiting factors. *Waste Manag.* **2015**, *40*, 44–52. [CrossRef]
48. Liu, Y.; Wu, L.; Baddeley, J.A.; Watson, C.A. Models of biological nitrogen fixation of legumes. A review. *Agron. Sustain. Dev.* **2011**, *31*, 155–172. [CrossRef]
49. Anglade, J.; Billen, G.; Garnier, J. Relationships for estimating $N_2$ fixation in legumes: Incidence for N balance of legume-based cropping systems in Europe. *Ecosphere* **2015**, *6*, art37. [CrossRef]
50. Rumpel, C.; Kögel-Knabner, I. Deep soil organic matter—A key but poorly understood component of terrestrial C cycle. *Plant Soil* **2011**, *338*, 143–158. [CrossRef]
51. Salome, C.; Nunan, N.; Pouteau, V.; Lerch, T.Z.; Chenu, C. Carbon dynamics in topsoil and in subsoil may be controlled by different regulatory mechanisms. *Glob. Chang. Biol.* **2010**, *16*, 416–426. [CrossRef]
52. Siedt, M.; Schäffer, A.; Smith, K.E.; Nabel, M.; Roß-Nickoll, M.; van Dongen, J.T. Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Sci. Total Environ.* **2021**, *751*, 141607. [CrossRef]
53. D'Hose, T.; Cougnon, M.; De Vliegher, A.; Willekens, K.; Van Bockstaele, E.; Reheul, D. Farm Compost Application: Effects on Crop Performance. *Compos. Sci. Util.* **2012**, *20*, 49–56. [CrossRef]
54. Termorshuizen, A.; Moolenaar, S.; Veeken, A.; Blok, W. The value of compost. *Rev. Environ. Sci. Biotechnol.* **2004**, *3*, 343–347. [CrossRef]
55. De Corato, U. Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: A review under the perspective of a circular economy. *Sci. Total Environ.* **2020**, *738*, 139840. [CrossRef] [PubMed]
56. Milinković, M.; Lalević, B.; Jovičić-Petrović, J.; Golubović-Ćurguz, V.; Kljujev, I.; Raičević, V. Biopotential of compost and compost products derived from horticultural waste—Effect on plant growth and plant pathogens' suppression. *Process. Saf. Environ. Prot.* **2019**, *121*, 299–306. [CrossRef]
57. Cavagnaro, T.R. *Biologically Regulated Nutrient Supply Systems*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 293–321.
58. White, K.E.; Brennan, E.B.; Cavigelli, M.A.; Smith, R.F. Winter cover crops increase readily decomposable soil carbon, but compost drives total soil carbon during eight years of intensive, organic vegetable production in California. *PLoS ONE* **2020**, *15*, e0228677. [CrossRef]
59. Abbott, L.K.; Manning, D.A.C. Soil Health and Related Ecosystem Services in Organic Agriculture. *Sustain. Agric. Res.* **2015**, *4*, 116. [CrossRef]
60. Pergola, M.; Persiani, A.; Pastore, V.; Palese, A.M.; D'Adamo, C.; De Falco, E.; Celano, G. Sustainability Assessment of the Green Compost Production Chain from Agricultural Waste: A Case Study in Southern Italy. *Agronomy* **2020**, *10*, 230. [CrossRef]
61. Bos, J.F.; Berge, H.F.T.; Verhagen, J.; Van Ittersum, M.K. Trade-offs in soil fertility management on arable farms. *Agric. Syst.* **2017**, *157*, 292–302. [CrossRef]
62. Poeplau, C.; Don, A. Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis. *Agric. Ecosyst. Environ.* **2015**, *200*, 33–41. [CrossRef]
63. Dannehl, T.; Leithold, G.; Brock, C. The effect of C:N ratios on the fate of carbon from straw and green manure in soil. *Eur. J. Soil Sci.* **2017**, *68*, 988–998. [CrossRef]
64. Schimel, J. The implications of exoenzyme activity on microbial carbon and nitrogen limitation in soil: A theoretical model. *Soil Biol. Biochem.* **2003**, *35*, 549–563. [CrossRef]
65. Kuzyakov, Y.; Friedel, J.; Stahr, K. Review of mechanisms and quantification of priming effects. *Soil Biol. Biochem.* **2000**, *32*, 1485–1498. [CrossRef]
66. Chmelíková, L.; Schmid, H.; Anke, S.; Hülsbergen, K.-J. Nitrogen-use efficiency of organic and conventional arable and dairy farming systems in Germany. *Nutr. Cycl. Agroecosystems* **2021**, *119*, 1–18. [CrossRef]
67. Rychcik, B.; Adamiak, J.; Wójciak, H. Dynamics of the soil organic matter in crop rotation and long-term monoculture. *Plant Soil Environ.* **2006**, *52*, 15–20.
68. Benbi, D.K.; Toor, A.; Brar, K.; Dhall, C. Soil respiration in relation to cropping sequence, nutrient management and environmental variables. *Arch. Agron. Soil Sci.* **2020**, *66*, 1873–1887. [CrossRef]
69. Cong, W.-F.; Hoffland, E.; Li, L.; Six, J.; Sun, J.-H.; Bao, X.-G.; Zhang, F.-S.; Van Der Werf, W. Intercropping enhances soil carbon and nitrogen. *Glob. Chang. Biol.* **2015**, *21*, 1715–1726. [CrossRef]